BBC

Science Focus

MAGAZINE

COLLECTION

SPACE

THE FINAL FRONTIERS

The missions that will unravel the mysteries of the Universe

Voyage to Venus, our fiery neighbour

A new race to the Moon has begun

The rover that will search for life on the Red Planet

The hunt for the oldest galaxies in the Universe

What will New Horizons discover beyond Pluto?

Secrets of the supermassive black hole

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EDITORIAL
Editor Daniel Bennett
Managing editor Alice Lipscombe-Southwell
Production assistant Holly Spanner
Commissioning editor Jason Goodyer
Staff writer James Lloyd
Editorial assistant Amy Barrett

ART & PICTURES
Art editor Joe Eden
Deputy art editor Steve Boswell
Designer Jenny Price
Picture editor James Cutmore

ADVERTISING & MARKETING
Group advertising manager Tom Drew
Advertisement manager Sam Jones
0117 300 8145 sam.jones@immediate.co.uk

LICENSING & SYNDICATION
Director of licensing & syndication Tim Hudson
International partners manager Anna Brown

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Production director Sarah Powell
Production co-ordinator Emily Mounter
Reprographics Tony Hunt, Chris Sutch

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BBC STUDIOS, UK PUBLISHING
Chair, editorial review boards Nicholas Brett
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Head of publishing Mandy Thwaites
Compliance manager Cameron McEwan
UK Publishing coordinator Eva Abramik
Contact UK.Publishing@bbc.com
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Welcome

When we first landed on the Moon in 1969, humankind collectively marvelled at the ingenuity of our species. We had explored the surface of our own planet and had now successfully set foot on another world as well – no problem was insurmountable for us. While we'd landed uncrewed craft on the Moon before that, and had already sent probes to Venus and Mars, it was arguably the Moon landing that energised us to continue exploring the cosmos, so we could unlock the secrets of the Universe and perhaps even life itself.

We set our sights further afield than the Moon, with missions to Mars, Jupiter, Saturn and beyond. But we also started building space stations that would allow us to explore the effects of space while remaining in comfortable proximity to our own planet.

Despite our efforts, however, many aspects of the cosmos remain a mystery. For example, despite all the missions to the Moon, we still know very little about its far side. That could soon change because China's Chang'e 4's craft successfully touched down in 2019 (p10). In January this year, they released their first set of data, which is now available for astronomers to pore over – in the process, they'll revolutionise our knowledge of our Moon. Mars has been the destination of choice in recent years, but we're still not sure if it hosts life, so later this year ESA will send a mission to the Red Planet to find out if it does (p26). And our other planetary neighbour, Venus, has been somewhat forgotten over the last few decades – that's why teams of scientists think it's high time we went back (p18).

Speaking of planets, we're still not sure if our Solar System hosts a huge ninth planet beyond Neptune, so we meet the scientists who are hunting for it (p60). Farther afield, in solar systems beyond our own, scientists are certain there could be Earth-like worlds. By using ingenious methods and a new breed of telescopes, they're sure they can spot them (p74).

Enjoy!

Alice

Alice Lipscombe-Southwell, Editor

Chang'e 4's lunar rover trundles across the surface of the Moon while the lander looks on

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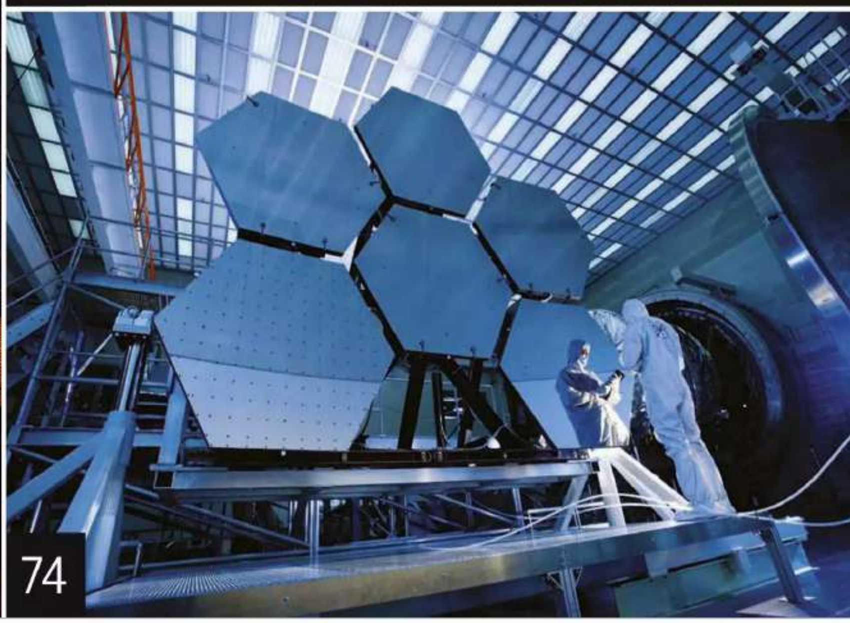


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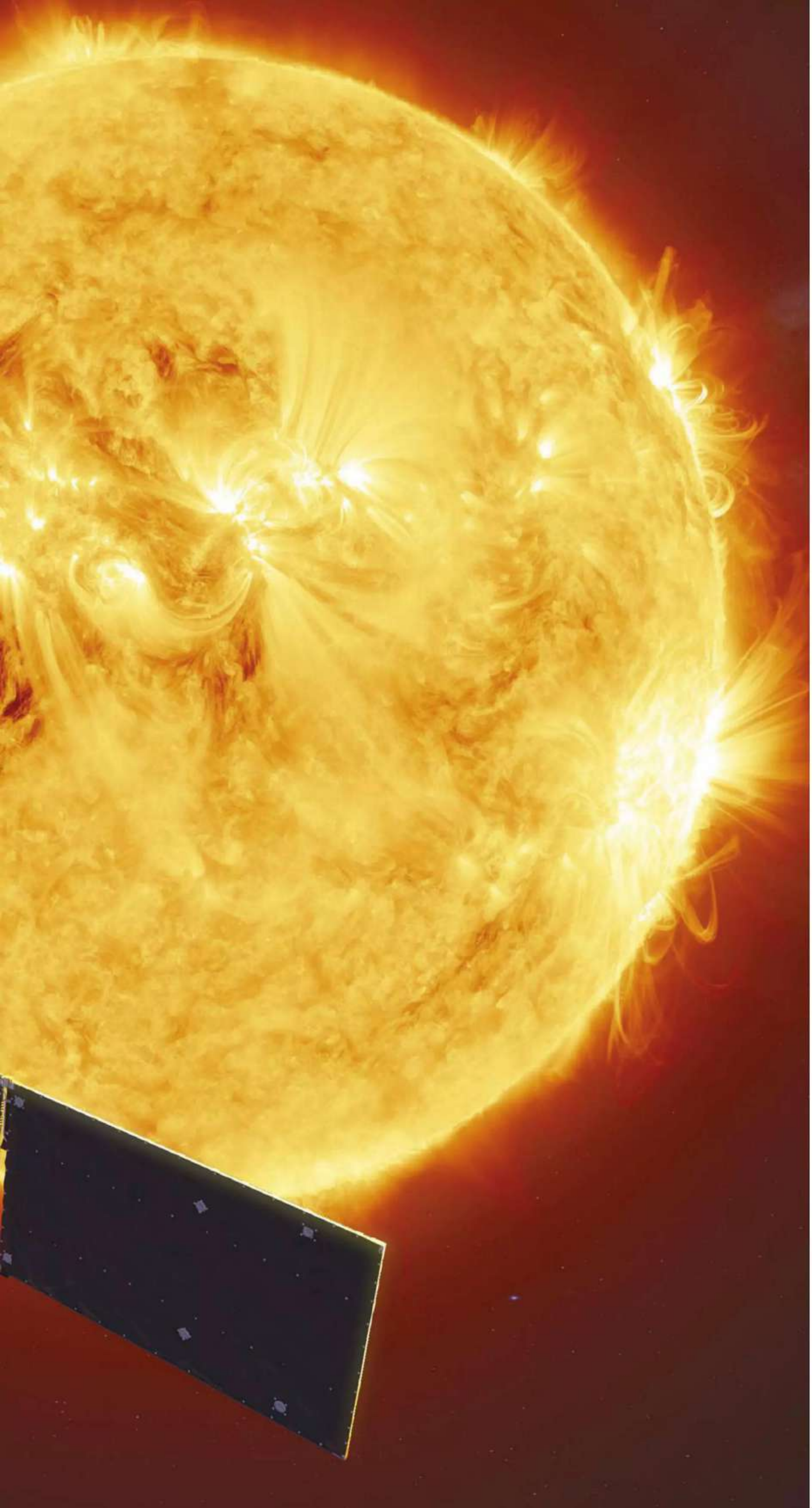


EYE OPENER

Sol mates

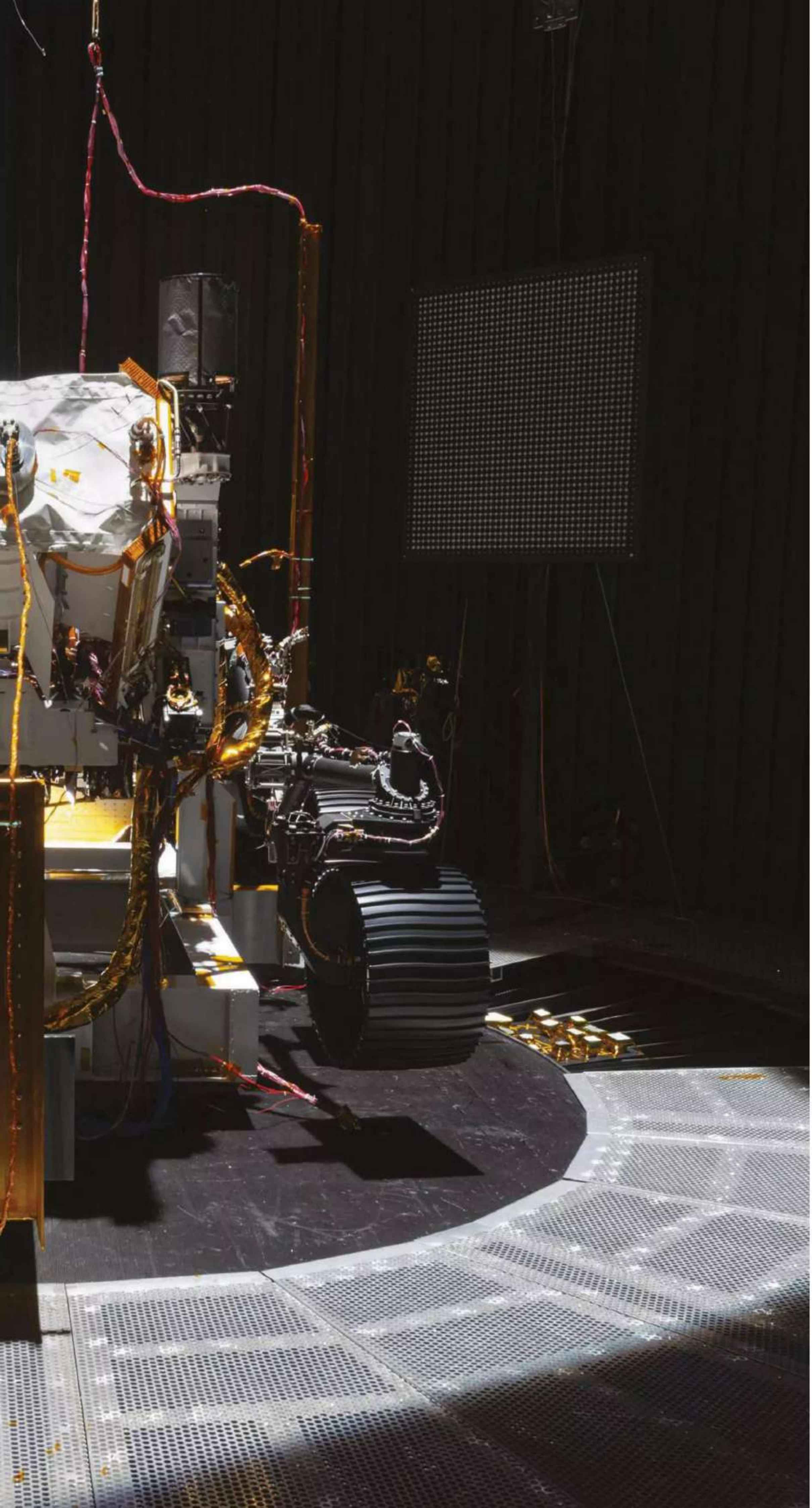
FLORIDA, USA

In the early hours of 6 February, Solar Orbiter will set off from Cape Canaveral in Florida to begin its journey to the Sun. This joint NASA and ESA mission will unravel some of the mysteries of the Sun, taking high-resolution photos of its polar regions for the very first time.

Data gathered by the probe will help us understand how our star creates and controls the heliosphere – a giant bubble of plasma that surrounds our Solar System – as well as investigating coronal mass ejections and solar winds.

During the mission, this spacecraft will be exposed to sunlight 13 times more powerful than we feel on Earth. To protect the inside of the probe from the intense heat and radiation, Solar Orbiter's instruments are hidden behind small 'peepholes' in the heat shield, which will close when not in use.

ESA



EYE OPENER

A light touch

CALIFORNIA, USA

An engineer uses a solar intensity probe to carefully measure the amount of artificial sunlight reaching different parts of NASA's Mars 2020 rover, at the Jet Propulsion Laboratory in California. Using this crucial data, scientists will be able to determine how this car-sized robotic scientist will interact with the Sun while on the Martian surface.

For the test, powerful xenon lamps were used to simulate the Sun, as the spectral output of xenon is similar to that of our star. The lamps were illuminated several floors below the craft, then bounced off a mirror at the top of the chamber onto the rover.

Based on the design of Curiosity, which landed on Mars more than seven years ago, this as-yet-unnamed mission will carry new instruments including a core drill and helicopter drone.

NASA/JPL

A NEW RACE TO THE MOON HAS BEGUN

INSIDE CHINA'S PLANS TO BUILD A LUNAR BASE

by COLIN STUART

Early January was the one-year anniversary of the first mission to land on the far side of the Moon – China's Chang'e 4. To mark the occasion, the Chinese space agency released the data and images they'd gathered so far.

Looking back to 3 January 2019, there was much excitement when China successfully lowered their Chang'e 4 mission onto the Moon's surface, and just 12 hours later, the Yutu 2 rover trundled down a ramp to imprint its tyre tracks in the lunar dust on the Moon's far side for the first time. "It's a hugely significant moment in the history of space exploration," says Prof Ian Crawford, a planetary scientist at Birkbeck University of London.

Chang'e is named after the Chinese goddess of the Moon, with Yutu being her pet white rabbit that is believed to be visible on the lunar surface, much like the man in the Moon here in the West. Chang'e 4 marked a return to the Moon's surface after years of human indifference, as we've strived to explore the rest of the Solar System.

Interest in all things lunar began to wane after the Apollo missions ended in 1972, with even robotic missions to the Moon's surface fizzling out by 1976. And so it remained until December 2013, when China landed the first Yutu rover on the near side of the Moon as part of the Chang'e 3 mission, making them only the third nation after the US and Russia to successfully dispatch and land a lunar rover.

But the Chang'e 3 mission wasn't without its difficulties, as a technical fault hampered the rover's movement not long after landing. The suspected culprit was more frequent encounters with rocks than originally envisioned. Considering these issues, the Chinese space agency's subsequent move was a brave one. "It's quite impressive that their next attempt was on the far side of the Moon," says Crawford.

Due to the Earth's gravitational pull, we only ever see one side of the Moon – the other is permanently turned away from us. That's why Chang'e 4 landed during a new Moon, a time when our side is dark and the far side is completely illuminated by the Sun. Regardless of which side they land on, missions to the Moon have to endure two weeks of cold darkness, followed by a fortnight of intensely bright daylight.

The only way to learn more about the far side is to send probes (or people) around the back for a closer look. While the first image of the far side was taken in 1959, it has taken until now to land a probe on it. NASA rejected the idea of sending Apollo 17, the last human landing mission, there in the 1970s, partly due to the difficulties with communication – the Moon itself blocks direct radio signals with Earth.

LUNAR LANDING

To get around the communications problems, the Chinese parked the Queqiao (Magpie Bridge) satellite in lunar orbit in 2018 to relay messages back home. Queqiao orbits 65,000 kilometres beyond the Moon and transmits signals back to China and other base stations around the world. This system makes the mission more of an intricate ballet than near side landings. Mission scientists spent four weeks prior to touchdown testing out this crucial relay system. The far side is also far more jagged compared to the relative smoothness of the near side, meaning there are even more potential hazards to avoid on landing. According to Prof Bernard Foing, executive director of the International Lunar Exploration Working Group, success required "a number of critical manoeuvres including launch, trans-lunar injection, lunar capture, de-orbiting, stabilisation and controlled descent, hazard avoidance, soft landing, the deployment and commissioning of rover and instruments." It all seems to have worked perfectly. "The whole process was as expected, the result was pretty precise and the landing was very stable," chief designer Sun Zezhou told Chinese state media shortly after confirmation of success reached home.

Their chosen landing spot was the 180km-wide Von Kármán crater, named after aerospace engineer Theodore von Kármán who made many key advances in the field of aerodynamics in the 20th Century. It's an impact site superimposed on a much bigger collision scar known as the South Pole-Aitken basin. "It is the Moon's largest, deepest, and oldest impact structure," says Foing. Place Mount Everest on the crater floor and its peak wouldn't be close to poking out over the top. It's of extreme geological interest as it could provide clues about the way the Moon formed from debris thrown into space after a small planet collided with the infant Earth. The crater was flooded with lava during the Moon's early days, meaning the crater floor is incredibly smooth and far less dangerous to land on than elsewhere on the far side. "It was very much chosen with safety in mind," says Crawford.

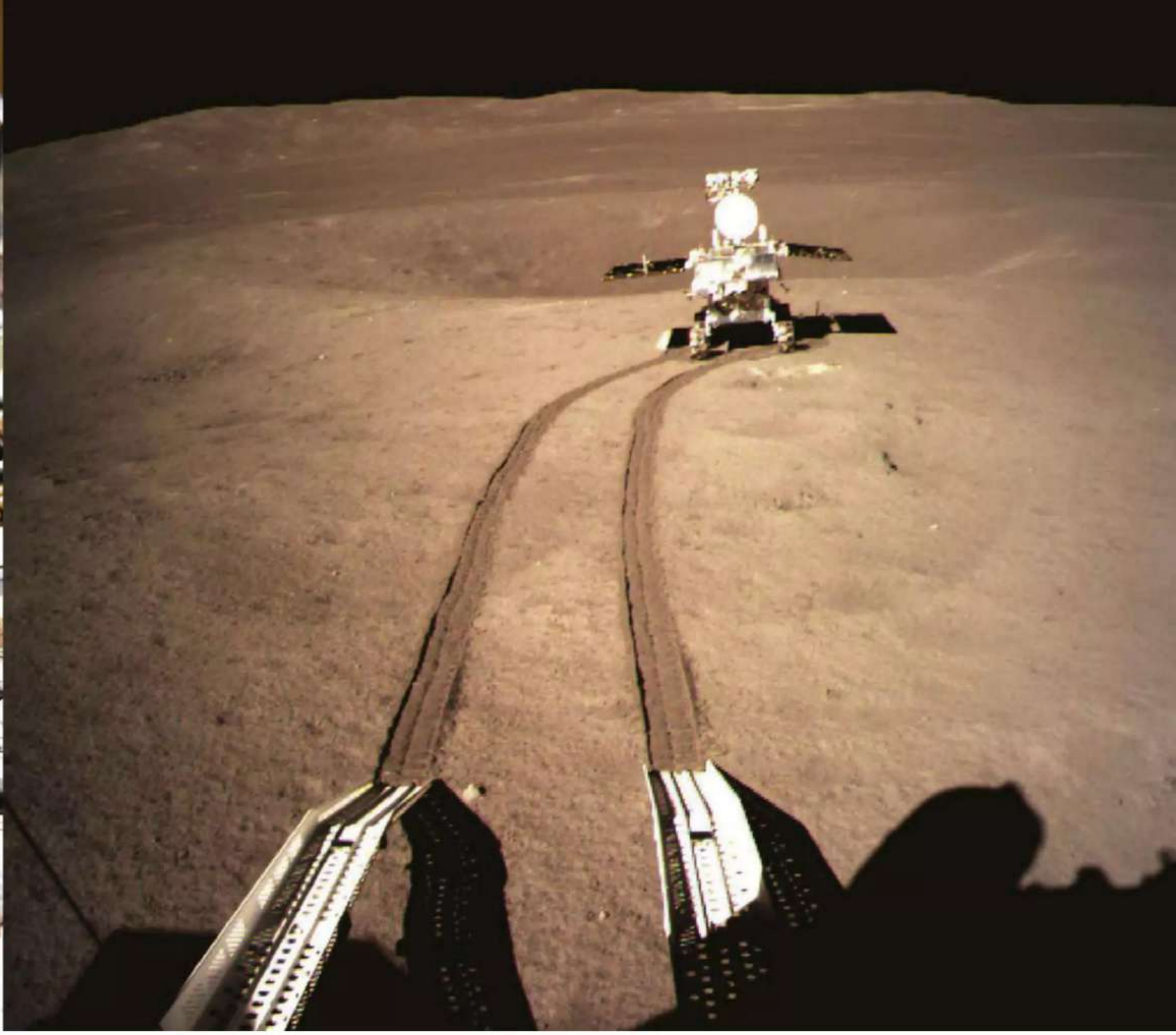
ABOVE
Technicians at Beijing's Aerospace Control Center celebrate Chang'e 4's successful landing on the Moon

ABOVE RIGHT
Selfie time! The Yutu 2 rover trundles across the Moon's surface, making fresh tracks as it goes

"WHILE THE FIRST IMAGE OF THE FAR SIDE WAS TAKEN IN 1959, IT HAS TAKEN UNTIL NOW TO LAND A PROBE ON IT"

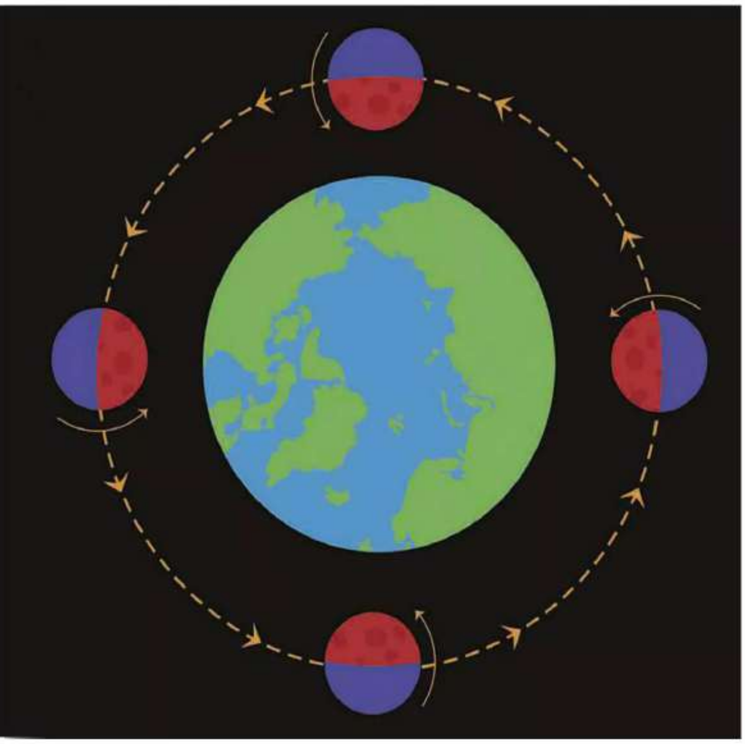
The colossal impact that formed the Aitken basin could well have penetrated deep into the Moon's mantle, exposing deeper basalt material onto the surface. "No one has ever measured the composition of far side basalt before," says Crawford. Doing so isn't a certainty, however, as the interesting stuff might have been covered over by the lava flows that flooded the basin. Like any space mission, Chang'e 4 scientists had to balance risk and reward. So they included another way to get data on the Moon's subsurface – the Yutu 2 rover carries an instrument called Lunar Penetrating Radar (LPR) that can scan the structure of the lunar far side down to a depth of 100 metres.

Geology is far from Chang'e 4's only aim. A wide array of other experimental instruments were also crammed onto the back of Chang'e

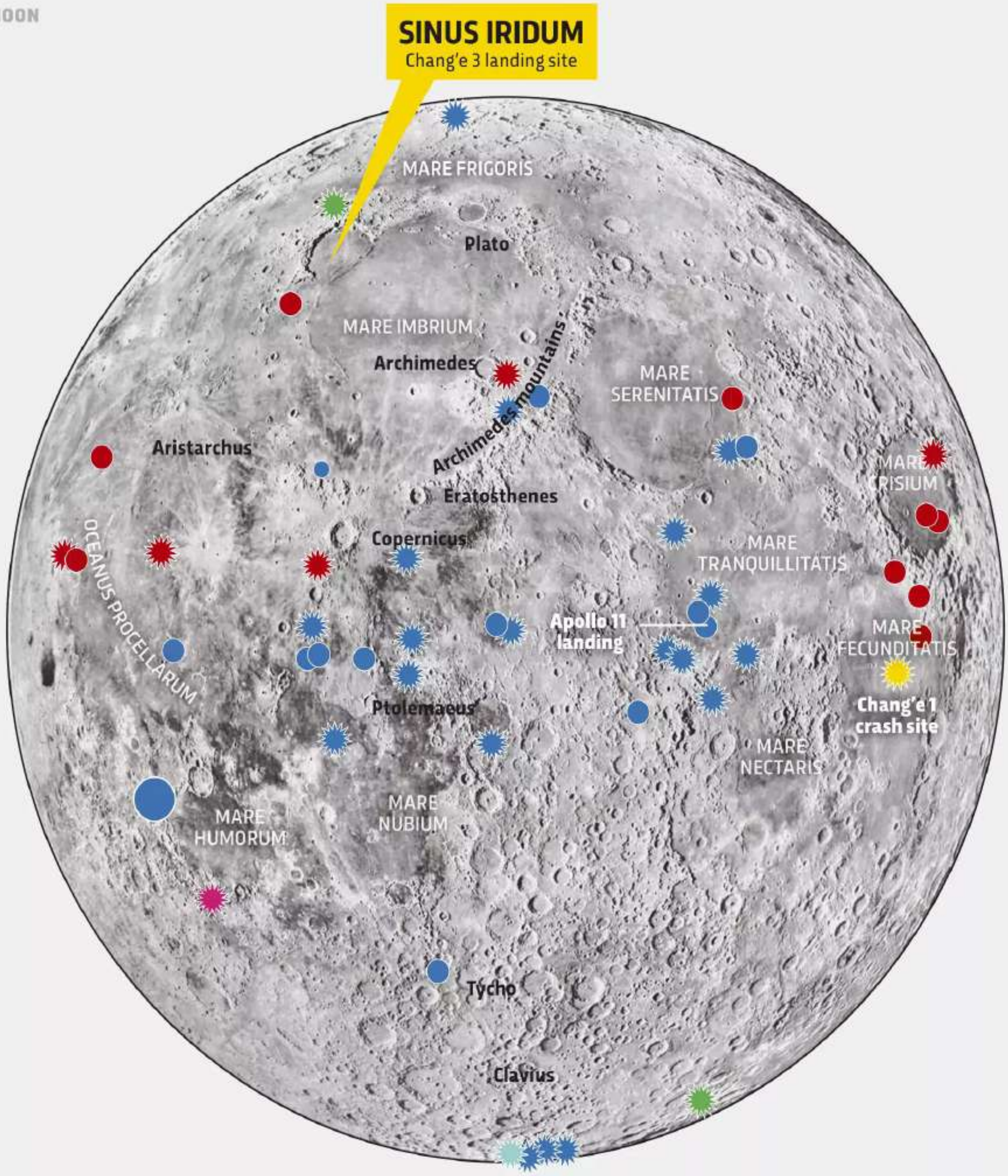


WHY DO WE ONLY EVER SEE ONE SIDE OF THE MOON?

Thanks largely to Pink Floyd's 1973 album, astronomers regularly contend with talk of the 'dark side of the Moon'. There isn't one. At least there's no permanently dark side of the Moon. It is true that we only ever see the front of the Moon and not the back due to an effect called tidal locking. Over time the Earth's gravity slowed the Moon's rotation on its axis until it matched the time it takes to orbit us (both 27.3 days). So the Moon is rotating, we just never see the other side. The Moon is always half lit up and half not (day and night, just like on Earth). Where this sunlight falls depends on the Moon's position around the Earth. When between us and the Sun, the back is completely illuminated – definitely not dark. The only time it is completely dark is when we are experiencing a full Moon.



SHUTTERSTOCK, CHINA NATIONAL SPACE ADMINISTRATION



LANDINGS AND CRASHES ON THE NEAR SIDE OF THE MOON

- USA
- USSR, RUSSIA
- CHINA
- JAPAN
- EUROPEAN SPACE AGENCY
- INDIA
- CRASH (INTENTIONAL OR ACCIDENTAL)

4 and carried to the Moon. The far side of the Moon is considered by many astronomers to be an ideal place to build a radio telescope. Sheltered from the background hum of the Earth by the Moon itself, any observatory there would be free to make sensitive measurements of faint astronomical radio signals. Chang'e 4 includes an instrument capable of listening to space across a wide range of frequencies. Should its results prove fruitful, Crawford believes it could usher in much more sophisticated radio astronomy missions in future. However, the majority of Chang'e 4's non-geological experiments are designed to scope out the possibility of future human missions back to the Moon. According to Foing, one experiment called ASAN "will study how the solar wind interacts with the lunar surface and perhaps even the process behind the formation of lunar water." The South Pole-Aitken basin is thought to be home to large quantities of water ice – a crucial resource for tomorrow's Moon dwellers. Would-be astronauts will also be unprotected from the harshness of space. They'd be prone to sizeable doses of radiation from solar storms and cosmic

MINING ON THE MOON

There could be rich rewards on the lunar surface

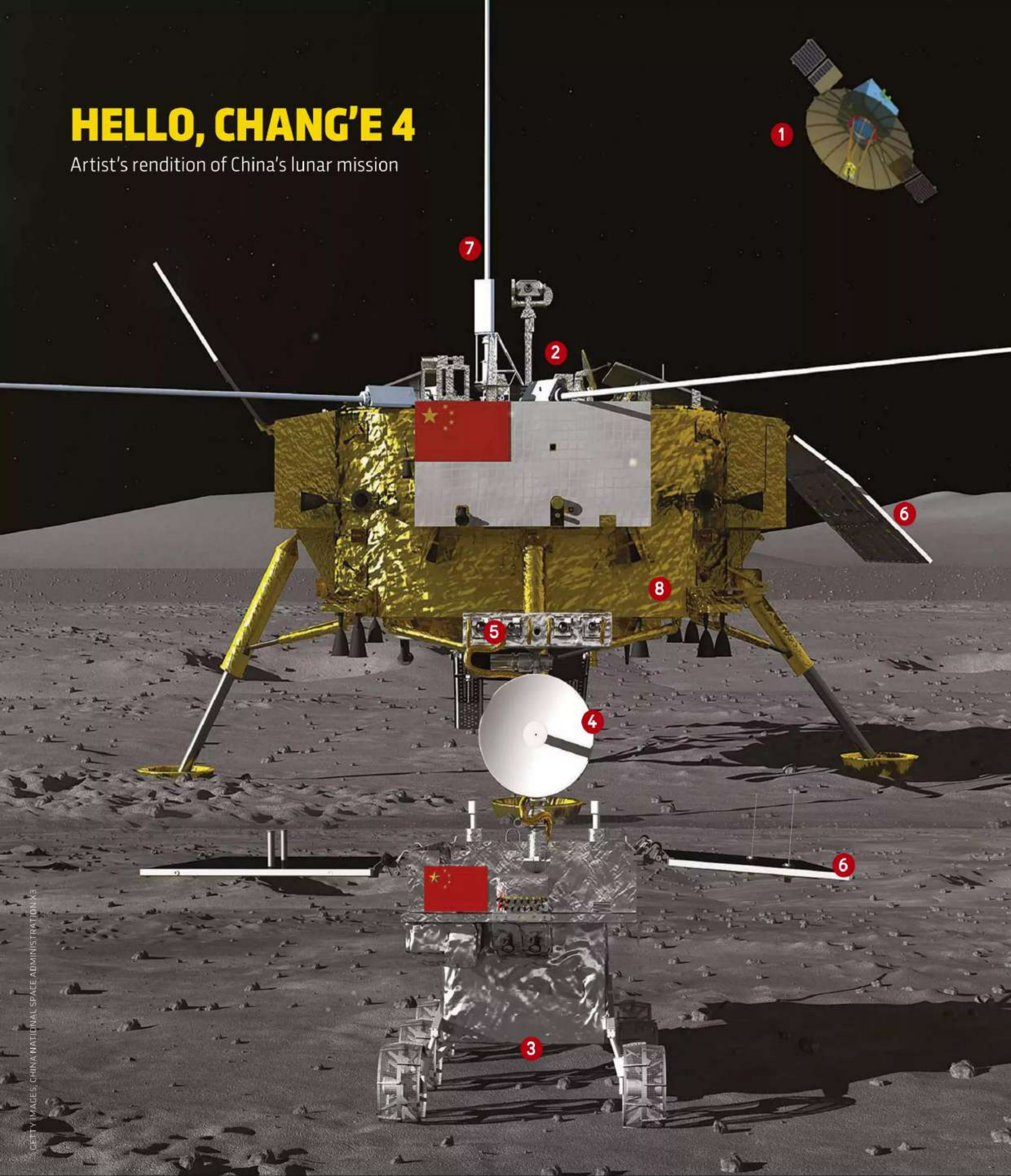
Why mine the Moon?
The Moon has a mass of 73 trillion tons. A crude calculation shows that if one ton of material were removed each day, it would take 220 million years to deplete the mass by 1 per cent. This isn't enough to cause a change in the Moon's orbit, or affect the gravitation that influences the tides on Earth. Geological surveys of the Moon show that it contains several vital elements that are in increasingly short supply on Earth. These include:

Helium-3
This substance is an isotope of helium that is made up of two protons and one neutron, rather than the two protons and two neutrons that comprise the more common helium-4. Though rare on Earth, helium-3 is relatively abundant in the Moon's soil and rock. It could play an increasingly important role in the future developments of energy generation, particularly as an energy source to power nuclear fusion reactors.

Rare earth metals
These 17 elements are commonly used in smartphones, computers and medical equipment. Rare earth metals are vital to emerging technologies, but around 90 per cent of the world's supply is produced in China, and experts say they have just 15 to 20 years' worth of supplies left. The Moon may become an increasingly important source of rare earth metals as supplies dwindle here on Earth.

HELLO, CHANG'E 4

Artist's rendition of China's lunar mission



1 Relay satellite This is positioned 65,000 kilometres beyond the lunar surface to bounce signals back to Earth.

2 Dosimeter This measures the radiation on the lunar far side, in preparation for future human missions to the Moon.

3 Ground-penetrating radar This can scan underneath the lunar surface, right down to a depth of 100 metres.

4 Transmitter dish This sends scientific data and images from the Yutu 2 rover to the relay satellite.

5 Panoramic camera This has already sent back stunning images of the landscape on the far side of the Moon.

6 Solar panels These provide power to the rover, but only during the two weeks every month when the far side is illuminated.

7 LFS booms This trio of five-metre-long antennas picks up radio waves from the early Universe, just after the Big Bang.

8 Lunar Micro Ecosystem The lander carries an experiment containing various seeds along with silkworm eggs, but it was called off after a few days.

● rays generated by stars exploding elsewhere in the Galaxy. The Lunar Lander Neutrons and Dosimetry (LND) experiment, developed in collaboration with Kiel University in Germany, assesses the strength of that dose in the vicinity of Chang'e 4's landing site.

LIFE ON THE MOON?

The experiment that fired our collective imaginations was the Lunar Micro Ecosystem. This small, sealed container housed various seeds, along with silkworm and fruit fly eggs. After landing, the experiment was powered up and the temperature adjusted to 24°C. A tiny camera kept watch to see if living things could eke out an existence in the harsh, alien environment. On 15 January 2019, it was reported that some of the seeds had sprouted, and images of the cottonseed seedlings were released. But the success was short-lived, when it was reported that the shoots had failed to survive the lunar night. None of the other organisms showed any signs of life and the experiment was called off a few days into its planned 100-day stint. Still, decades from now, humans could look back at this experiment as the beginning of life on the Moon. Make no mistake that is what China is gearing up for. Their recent launches are following roughly the same pattern as NASA before the Apollo era. First, launch satellites to the Moon (Chang'e 1 and 2), then land a rover on the near side (Chang'e 3). This far side landing is a real show of intent. "The Chang'e 4 mission will advance [their] technical maturity for future robotic and human landings," says Foing.

China wants to be considered in the same league as the US and Russia when it comes to space exploration. Yang Liwei became the first Chinese astronaut (also called a taikonaut) in 2003. So far, 12 taikonauts have been into space, some of whom were sent to a prototype Chinese space station called Tiangong-1, which remained functioning around Earth from 2011 to 2018 before falling from orbit over the southern Pacific Ocean and reportedly burning up in the atmosphere. Now, the Chinese have begun the construction of a new, more ambitious orbital outpost in a bid to match the stature of the long-established International Space Station. They hope to have it finished by 2022. What they learn there, combined with the lessons from Chang'e 4, could see China send the first taikonauts to the Moon as early as 2025. In the meantime, more robotic missions are already in the pipeline. "Their next steps will be Chang'e 5 and 6," says Foing. The former is scheduled to launch this year and will aim to return samples of lunar material from the near side.

"DECADES FROM NOW, HUMANS COULD LOOK BACK AT THIS EXPERIMENT AS THE BEGINNING OF LIFE ON THE MOON"

ABOVE LEFT
Yang Liwei, the first Chinese astronaut (also called a taikonaut), waves to the crowds after stepping out of the Shenzhou-5 re-entry capsule in October 2003

ABOVE
Tiangong-1, China's first space station, orbited the Earth between 2011 and 2018

GETTY IMAGES, CHINA MANNED SPACE ENGINEERING OFFICE

Success will demonstrate that the Chinese can return material from the Moon, paving the way to bring humans back too. "A number of other robotic landers are planned that could build up a de facto lunar robotic village," says Foing.

SPACE RACE

There is another potential advantage to be gained from the recent Chang'e missions. No other country has landed anything on the Moon since the 1970s. Having readily available technology to do so could place China in the lead to exploit the Moon's natural resources. By analysing the composition of the lunar far side, they could gain valuable information about the kind of treasures potentially on offer. The Moon is already thought to contain significant amounts of helium-3, which is a chemical that's exceedingly rare on Earth. What else could they find squirrelled away in these unexplored rocks? Could a modern space race be triggered as superpowers compete once again for off-Earth supremacy? Some quarters are nervous about what it could mean for the potential Chinese militarisation of space. The country is party to the 1967 Outer Space Treaty, which forbids signatories from placing weapons of mass destruction on the Moon. However, China has previously flexed its space muscles, most notably when it destroyed one of its own weather satellites in 2007 using a missile fired from the ground. While other space agencies have been quick to congratulate the Chinese on their latest success, and talk openly about potential joint projects, it remains to be seen whether the future will be more about competition or cooperation. **SF**

THE NEW SPACE RACE?

The success of China's Chang'e 4 landing has again brought the country's space programme into the spotlight, and raised the question whether China is now a serious player in space exploration. The answer is unequivocally 'yes'. While it is easy to rebuff these latest accomplishments by pointing out that the United States and Russia landed spacecraft on the Moon more than half a century ago, this misses the point.

Though they did not generate as many column inches as Chang'e 4, there were 39 Chinese rocket launches in 2018, only one of which failed. In comparison, Russia launched 20 rockets, with one failure; and the United States launched 34, all successful. Europe lagged behind with eight launches with one failure, while Japan and India launched six and seven rockets respectively.

It looks likely that China's position will become increasingly difficult to ignore, particularly as the country is open for collaboration – Chang'e 4 carries experiments from Swedish, German, Dutch and Saudi Arabian researchers. In 2017, the Chinese announced plans for a permanently crewed space station as part of their Tiangong or Heavenly Palace programme. Notably, the country signed an agreement with the United Nations to allow experiments and astronauts from other countries to use the station. The core module of the space station is planned to be launched in 2020 with proposals for collaborations coming from 27 countries. It's unlikely, however, that the US will be involved as Congress banned NASA from using its funds to host Chinese visitors in 2011.

This division between the superpowers leads to the question of rivalry and whether China's interest in the Moon will spark a new space race. It's complicated. The same team of space agencies responsible for the International Space Station (NASA, ESA, Russia's Roscosmos, Japan's JAXA, and Canada's CSA) are already developing the Lunar Orbital Platform-Gateway (LOP-G). LOP-G is a space station that would carry a four-person crew in an orbit around the Moon, sometime after the mid-2020s. But there are those who say it is a costly distraction from sending astronauts to Mars. So if anything, the Chinese interest in the Moon could lead these critics to call for efforts to be concentrated on Mars, in order to reassert NASA's lead in space. Such a plan, however, would inevitably bring NASA into disagreement with its international partners, all of whom are known to favour going to the Moon.

So the future is going to be interesting. Unlike the space race of the 1960s, when the United States and Russia went head-to-head to land on the Moon, we are likely to see two parallel space programmes develop, one led by NASA and the other by the Chinese. And although we are unlikely to see direct rivalry in their goals, you can be sure that both sides will be keeping an eye on each other.

by COLIN STUART *(@skyponderer)*

Colin is an astronomy writer. His latest book, How To Live In Space *(£16.99, Andre Deutsch), is out now.*

ILLUSTRATION: ANDY POTTS

VOYAGE TO VENUS

Scientists want to return to Venus, so they can try to find out why it morphed from a pleasant planet into a fiery and inhospitable hell hole

by ABIGAIL BEALL

We have a toxic twin. Venus is the closest planet to Earth, both in size and often in distance, yet the surface conditions couldn't be more different. One planet is home to abundant life; the other is hellishly hot, choked by an atmosphere of carbon dioxide that creates a surface pressure equivalent to being almost one kilometre underwater on Earth.

However, things weren't always this way. Once upon a time, Venus might have had a similar climate to Earth, complete with water oceans and plate tectonics.

Finding out what went wrong with Venus is the question behind a fresh surge in missions to explore the planet. It's an endeavour that promises to shed new light on how planets become habitable, and could even guide our search for life elsewhere in the cosmos.

BBC SOUNDS

Listen to former NASA chief scientist Ellen Stofan talking about her research into Venus in this episode of *The Life Scientific*
bit.ly/LS_ellenstofan

"FOUR AND A HALF BILLION YEARS AGO, THINGS LOOKED DIFFERENT. YOU'D SEE WATER AND A PLEASANT CLIMATE ON MARS, EARTH AND VENUS"

Over the past 20 years, exploration of Venus has fallen out of favour. Missions to Mars, Jupiter, Saturn and Pluto have dominated the headlines, and poor old Venus has become something of a forgotten planet. But this wasn't always the case. In fact, in the early days of space exploration, Venus was our first target...

EARLY EXPLORERS

In 1962, NASA's Mariner 2 spacecraft flew past Venus, becoming the first space probe to encounter another planet. Five years later, the Soviet Venera 4 probe entered the Venusian atmosphere, becoming the first to enter the atmosphere of another world. The same year, NASA's Mariner 5 set off on the space agency's second successful flyby mission. The exploration of Venus was in full swing.

What followed was a series of missions, some failures but mostly successes, to find out more about this planet that, at first glance, appeared so similar to our own. But from the 1980s onwards, the pace slowed down considerably. NASA's last dedicated mission to Venus was the Magellan spacecraft, which launched in 1989. The reason for this drop-off? As the data started to come back from our twin planet, astronomers interpreted the high temperatures, suffocating atmosphere and impact craters they saw on the surface as evidence that Venus was biologically and geologically dead – and therefore of limited interest to scientists searching for extraterrestrial life or Earth-like geology. The pristine condition of most of Venus's impact craters, for instance, indicated a comparatively young surface, which suggested that some kind of global, volcanic event in the planet's history had completely resurfaced the planet, resulting in a dramatic reduction in geological activity.

This idea, however, is still up for debate. "Since then, a lot of people have done [computer] modelling that indicates that this is a very unlikely interpretation," says Dr Sue Smrekar, a planetary geophysicist at NASA's Jet Propulsion Lab, and self-confessed 'Venusophile'. Instead of one huge event, says Smrekar, "you could have 'steady state' [smaller and reoccurring] processes of volcanism to produce the impact crater record." Settling this

ABOVE LEFT
Earth and Venus are extremely similar in size, giving them the moniker of the 'twin planets'

ABOVE
NASA's Mariner 2 flew past Venus in 1962 and was the first space probe to encounter another planet

NASA X3

debate, and discovering the true story of Venus's history, is the motivation behind a proposed NASA mission that's being led by Smrekar, called VERITAS.

SAME PLANET, DIFFERENT CLIMATE

Today, the average surface temperature on Venus is 462°C. But the planet wasn't always such a hot mess. When the Solar System was in its early stages, four and a half billion years ago, things looked different. "You'd see water and a pleasant climate on Mars, Earth, and Venus, most likely," says Dr Richard Ghail at Royal Holloway, University of London, who is lead scientist of a proposed European Space Agency (ESA) mission to Venus, called EnVision.

Two billion years later, it was a different story. Mars was basically dead and Earth was a frozen snowball, says Ghail. Earth was active as a planet, in the geological sense, but frozen solid, resembling how Jupiter's moon Europa looks today.

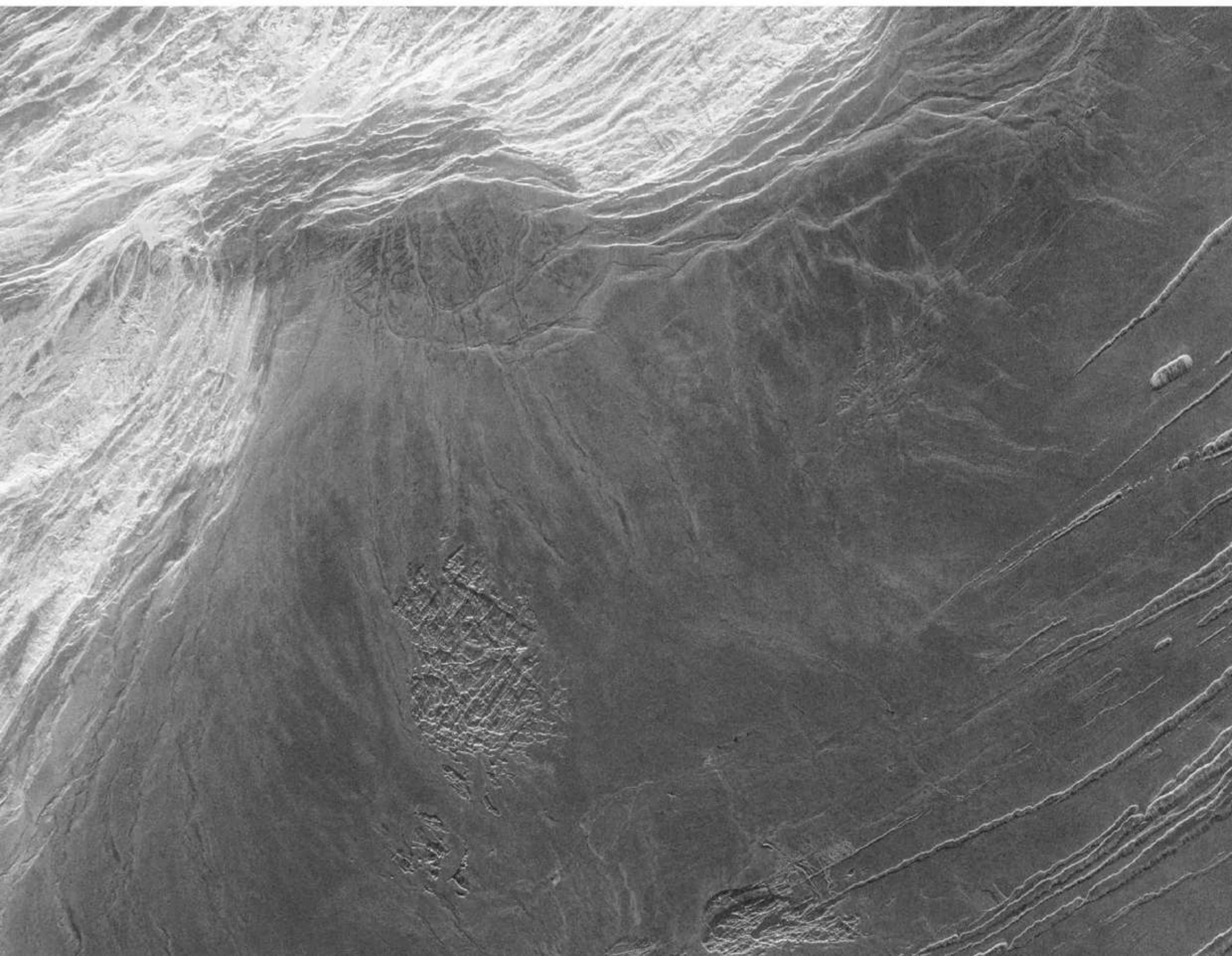
"Venus probably looked like a hot version of the Earth," says Ghail. "It still had oceans but they were evaporating... it was starting to get really unpleasant." At this point, "you'd think all three of these planets were doomed biologically. And yet, Earth came out of that and into this new phase where life appeared," he adds.

Understanding Venus's geological history will be crucial to piecing together the contrasting fortunes of the two planets. While Venus is not known to be geologically active today, its past patterns of volcanic activity will be a vital clue in helping us find out more about the planet. The amount of volcanism could be linked to the amount of toxic sulphur dioxide in Venus's atmosphere, for example, which is a key reason why it is uninhabitable. "Ultimately, we want to understand why Venus and Earth are different," says Smrekar.

The surface of Venus has not been mapped since NASA's 1989 Magellan mission. "We now have better topography maps for Pluto than we do for Venus, so it's time for an update," says Smrekar.

This is where VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) comes in. The aim of this mission, which is ➜

BELOW
The Maxwell Montes mountain range on Venus includes the planet's highest point, Skadi Mons



DESTINATI

VENUS

AVERAGE DISTANCE FROM SUN: 108,200,000KM

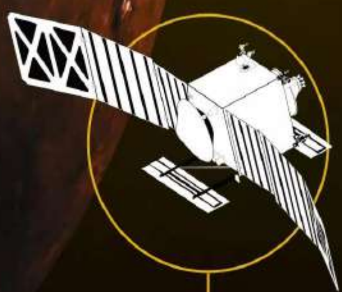
RADIUS: 6,052KM

MASS: 4.87×10^{24}KG

AVERAGE SURFACE TEMPERATURE: 462°C

PROPORTION OF CARBON DIOXIDE IN ATMOSPHERE: 96.5 PER CENT

SURFACE PRESSURE: 92 BAR



SHUKRAYAAN-1

POSSIBLE LAUNCH DATE: 2023
SPACE AGENCY: ISRO (INDIA)
AIM OF MISSION: ORBITER TO STUDY THE SURFACE AND ATMOSPHERE OF VENUS, POTENTIALLY INCLUDING RADAR, A PLASMA WAVE DETECTOR AND A CLOUD MONITORING CAMERA.

VERITAS

POSSIBLE LAUNCH DATE: 2021
SPACE AGENCY: NASA
AIM OF MISSION: ORBITER TO CAPTURE GLOBAL, HIGH-RESOLUTION MAPS OF TOPOGRAPHY AND ROCK TYPE ON THE PLANET'S SURFACE.

DAVINCI

POSSIBLE LAUNCH DATE: 2021
SPACE AGENCY: NASA
AIM OF MISSION: DESCENT PROBE TO UNDERSTAND THE HISTORY OF VENUS'S ATMOSPHERE AND STUDY THE CHEMICAL PROCESSES IN THE LOWER ATMOSPHERE.

EXPLORATION OF VENUS: THE HIGHLIGHTS SO FAR

DEC 1962

NASA's Mariner 2 is the first successful flyby mission of Venus – or any planet – sending back information about the Venusian atmosphere.

OCT 1967

Venera 4 is the first successful Soviet mission to Venus. The space probe carries out the first chemical analysis of the planet's atmosphere, revealing it to be mostly carbon dioxide.

JUL 1972

The Soviet Venera 8 is the first space probe to successfully land on the surface of Venus. It sends back data for 50 minutes.

OCT 1975

Venera 9 is the first spacecraft to orbit Venus, while its accompanying lander is the first to send pictures from the surface of another planet.

DEC 1978

Pioneer Venus 1 is NASA's first Venus orbiter, carrying out a range of tasks including mapping the planet's surface and measuring its magnetic field.

ON VENUS

EARTH

AVERAGE DISTANCE FROM SUN: 149,600,000KM

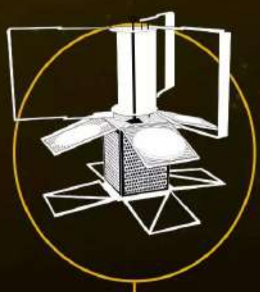
RADIUS: 6,371KM

MASS: 5.97 × 10^{24}KG

AVERAGE SURFACE TEMPERATURE: 14°C

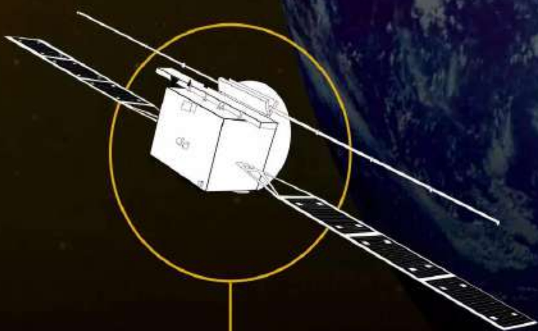
PROPORTION OF CARBON DIOXIDE IN ATMOSPHERE: 0.04 PER CENT

SURFACE PRESSURE: 1.01 BAR



LLISSE

POSSIBLE LAUNCH DATE: 2023
SPACE AGENCY: NASA
AIM OF MISSION: SMALL PROBE CAPABLE OF SURVIVING ON THE SURFACE OF VENUS FOR DAYS, CAPTURING INFORMATION ABOUT THE PLANET'S WEATHER.



ENVISION

POSSIBLE LAUNCH DATE: 2032
SPACE AGENCY: ESA
AIM OF MISSION: ORBITER TO STUDY VENUS'S ATMOSPHERE, HISTORY AND CLIMATE USING RADAR IMAGING.

VENERA-D

POSSIBLE LAUNCH DATE: 2026 - 2031
SPACE AGENCY: ROSCOSMOS (RUSSIA)
AIM OF MISSION: ORBITER, FOR DETAILED OBSERVATIONS OF THE PLANET'S ATMOSPHERE; LANDER, TO SPEND AT LEAST TWO HOURS ON THE SURFACE.

JUN 1985

The Soviet space probes Vega 1 and Vega 2 send landers down to Venus, before using the planet's gravity to carry out a flyby of Halley's Comet.

AUG 1990

NASA's Magellan spacecraft enters orbit around Venus, where it stays for four years, carrying out high-resolution radar mapping of the planet's entire surface.

APR 2006

ESA's Venus Express enters orbit around Venus, and is the first spacecraft to carry out long-term observations of the planet's atmospheric dynamics. It finds evidence for an ozone layer, lightning, and a huge, shape-shifting vortex at the planet's south pole.

DEC 2015

The Japanese Akatsuki space probe enters orbit around Venus after a previous failed attempt in 2010. It is currently studying the planet's atmospheric dynamics and cloud structure.

currently being considered for funding by the agency's Discovery Program (a series of lower-cost missions to explore the Solar System), is to use radar and measurements of the planet's thermal properties to produce high-resolution topography maps and information on rock types across the planet's entire surface. This will help to pin down the nature of Venus's volcanic past, but also answer the question of whether it ever had plate tectonics, and what role water played in its history.

Venus's surface has a handful of huge plateaus. "If these features are similar in composition and origin to those on the Earth, it tells us that Venus underwent some very Earth-like processes, and that water was really important in shaping the [Venusian] surface," says Smrekar. She adds that by examining the types of rock on Venus, we could discover whether or not water was once there. For example, certain rock types can only be created when lava meets water. Meanwhile, studying whether Venus's surface is broken up into continent-like features will show whether it once had plate tectonics. On Earth, plate tectonics play an important role in the carbon cycle, helping to remove carbon dioxide from the atmosphere. So a lack of plate tectonics on Venus could help to explain why this planet's atmosphere contains so much carbon dioxide (96.5 per cent), which is in turn responsible for Venus's runaway greenhouse effect.

ABOVE LEFT
The LLISSE probe, visualised here, is pencilled for launch in 2023 and would be able to survive on Venus's surface

ABOVE
Venus, illustrated here, has the hottest surface of any planet in the Solar System

VERITAS is just one of a suite of missions being proposed to explore Venus. Another in NASA's Discovery Program is DAVINCI (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging). If selected, this mission would involve dropping a descent probe through the atmosphere and measuring the chemical composition down to the surface in high-fidelity, providing information on the origin and evolution of the Venusian atmosphere, and helping to answer the question of why it's different to that of Earth. DAVINCI lost out to two other missions, Psyche and Lucy, in the 2015 round of proposals, but was resubmitted in July this year.

Meanwhile, another proposed NASA project, not connected to the Discovery Program, is LLISSE (Long-Life In-situ Solar System Explorer). This began in 2017 as a project to develop small landers and instruments capable of surviving on the surface of Venus for days, as opposed to the minutes of previous missions.

"This capability will revolutionise our understanding of Venus by allowing us to see how conditions change over time, giving us new insight into the dynamic processes occurring in Venus's atmosphere," says Dr Lori Glaze, director of NASA's Planetary Science Division, and part of NASA efforts to support LLISSE. "Such information is critical to getting at the history of water and possibly habitable periods in Venus's past. But this requires electronics that can survive temperatures of over 470°C."

Standard, silicon electronics break down quickly under these conditions, so LLISSE would use cutting-edge silicon carbide semiconductors. The aim is to have a probe on the surface of Venus,

"WE NOW HAVE BETTER TOPOGRAPHY MAPS FOR PLUTO THAN WE DO FOR VENUS, SO IT'S TIME FOR AN UPDATE"

NASA/GRC, SCIENCE PHOTO LIBRARY, ESA/AOES MEDIALAB

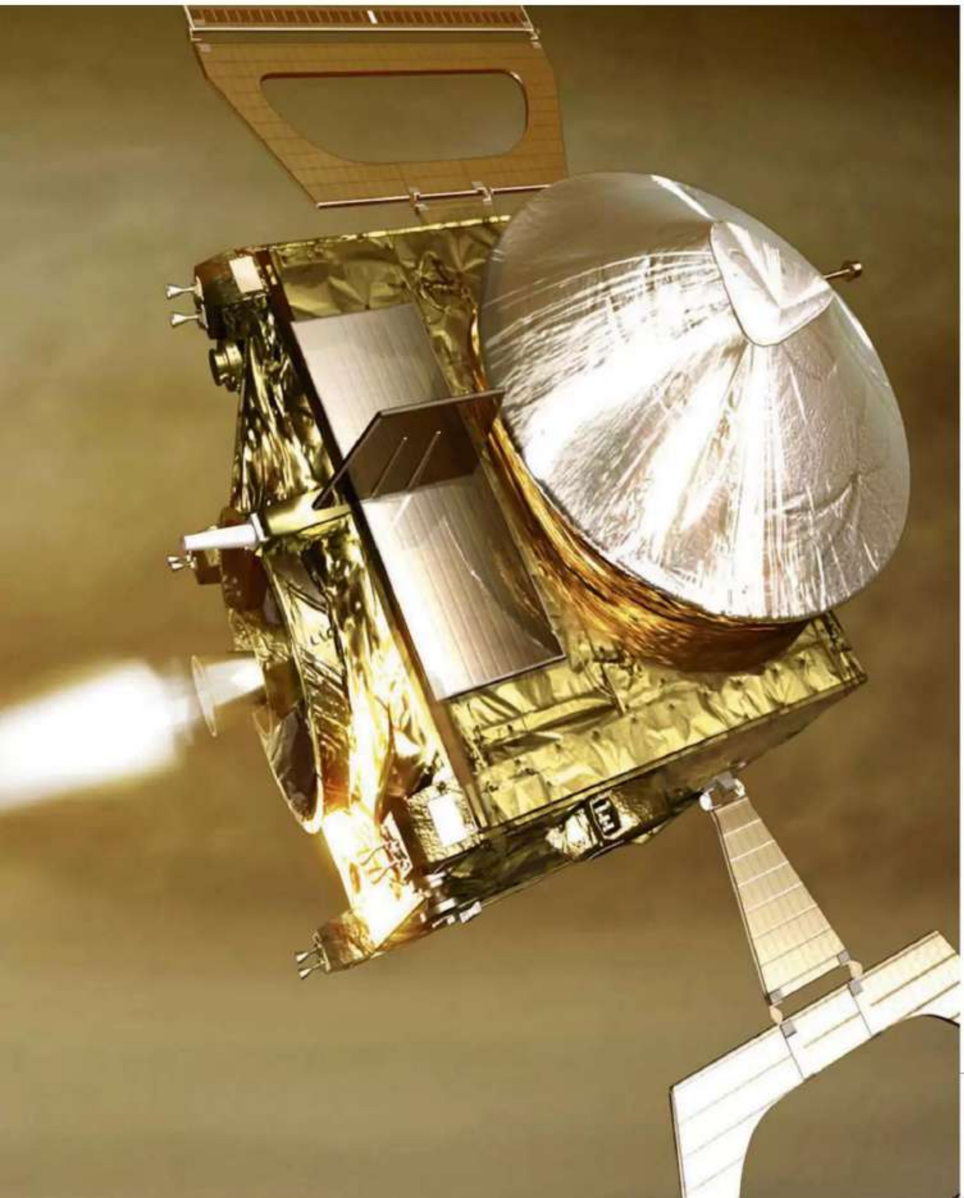
collecting data about the planet's weather in situ – something that would be a breakthrough moment for space exploration.

FUTURE OUTLOOK

Presently, none of these missions are set in stone. Out of all the proposed Solar System missions in NASA's Discovery Program in 2019, five will reach the next stage of development, and one will ultimately go ahead, with a launch slated for 2021. Meanwhile, it's hoped that the LLISSE probe will be ready to go in 2023, likely taken to Venus by another mission.

ESA also wants to study the Venusian surface using radar. The EnVision spacecraft would spend four years orbiting the planet, looking at how much volcanism is taking place and whether the surface is moving, and characterising the interior structure of the planet, too. All of this will help to build a more detailed picture of the differences – and similarities – between Venus and Earth. "It would be really exciting to do real comparisons with Earth," says Ghail, referring to the fact that the Venus data will be of a similar resolution to the geological data we already have for Earth.

BELOW
Venus Express, visualised here, was the first ESA mission to explore the second planet from the Sun



Part of the EnVision mission would include trying to spot the Soviet Venera landers, which sent images of the surface back to Earth. "We want to identify where they are [after they crash-landed on the surface], and then image their immediate surroundings to make sense of the images," says Ghail. This will enable researchers to link the chemistry of the rocks the landers analysed to a specific area on Venus.

EnVision is currently in its first phase of study, which will end in spring 2021. If it is selected, it will launch in 2032, arriving at Venus after a five-month cruise. But NASA and ESA are not the only space agencies with their eyes on Venus. Russia wants to continue its exploration of the planet with Venera-D, a proposed mission which includes an orbiter and a lander. And the Indian Space Research Organisation (ISRO) is planning an orbiter too, called Shukrayaan-1.

All of these missions promise to help us answer the question of how Venus became so different from Earth. But they also have their eye on an even bigger question: is there life elsewhere in the cosmos? Once we have a better idea of the processes that can make a planet habitable, exoplanet hunters will have a better idea of where to look for life on other worlds.

"We need to understand what happened to Venus, and how common this fate is, to estimate how many potentially habitable planets there are," says Prof Abel Méndez, director of the Planetary Habitability Laboratory at the University of Puerto Rico at Arecibo.

More clues will come as astronomers improve their ability to detect and measure exoplanet atmospheres. "We can't tell the Earths from the Venuses right now," says Méndez. A fundamental difference between the two planets is Venus's suffocating, extra-thick atmosphere. This [thickness] is "something we can't measure yet for any Earth-sized planet, but we are getting closer," he says.

Once astronomers have more information about exoplanet atmospheres, they'll be able to combine this with measurements of the planet's distance from its host star in order to gain a better prediction of how likely it is to be habitable. Because, as Earth and Venus have shown, distance isn't everything. "Even Earth with a Venus-like atmosphere would be too hot for life," says Méndez.

It may be a while before we have definitive answers to how many Venuses there are in the cosmos, and why two planets so close to each other could have such vastly different fates, but it seems that the gaze of the world's astronomers is finally turning back towards our closest neighbour. Sometimes, it turns out that the most interesting things are lying right under our noses. **SF**

by **ABIGAIL BEALL** *(@abbybeall)*
Abigail is a science journalist, based in Leeds.

ESA's Martian rover readies for launch

Ahead of its mission to search for life on the Red Planet, the European Space Agency's Rosalind Franklin rover was sent for a raft of extensive tests in Turin, Italy

by JASON GOODYER

THE MISSION

LAUNCH DATE:
26 July–13 August 2020

LAUNCH SITE:
Baikonur Cosmodrome, Kazakhstan, on a Russian Proton-M launcher

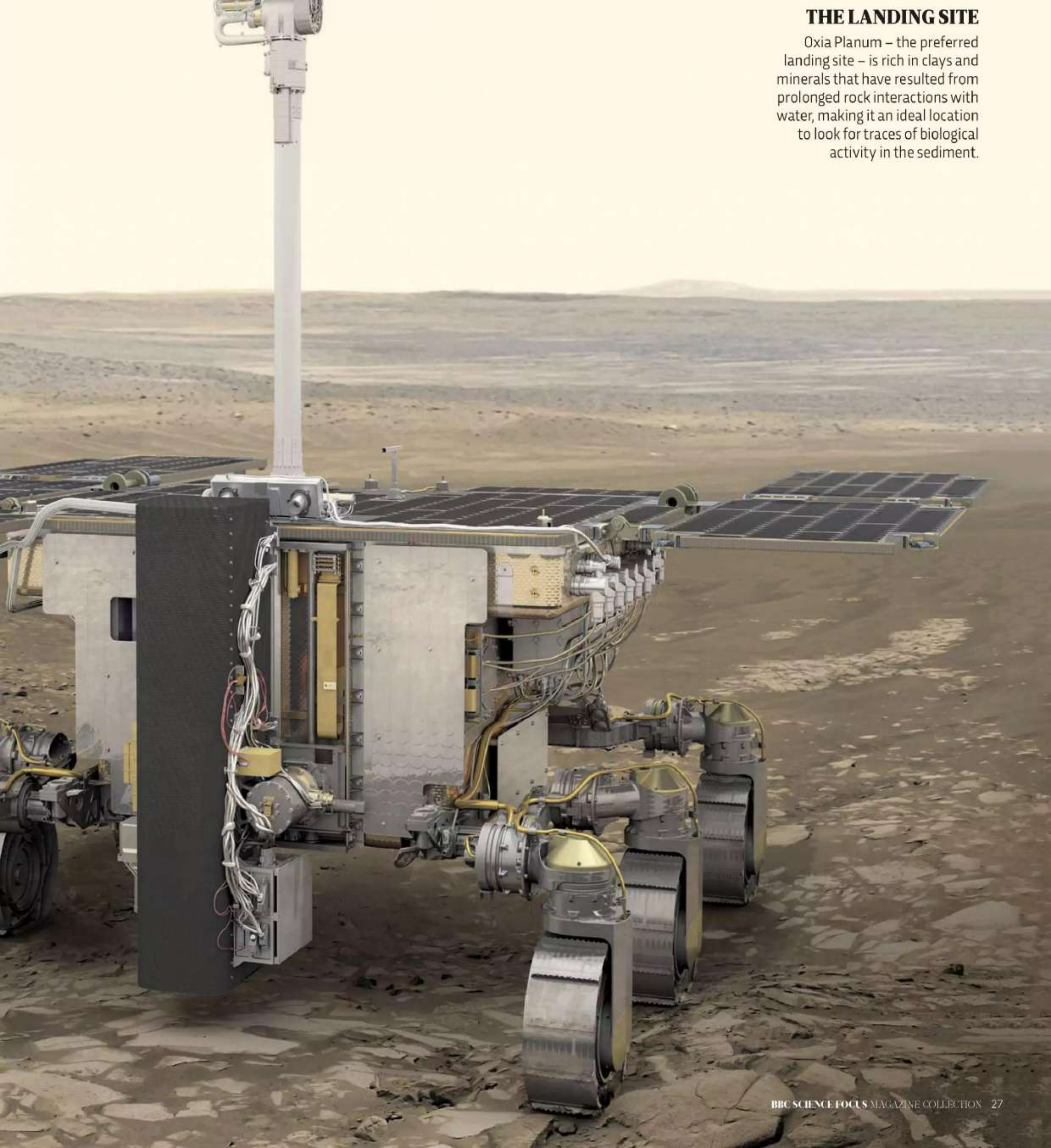
LANDING DATE: March 2021

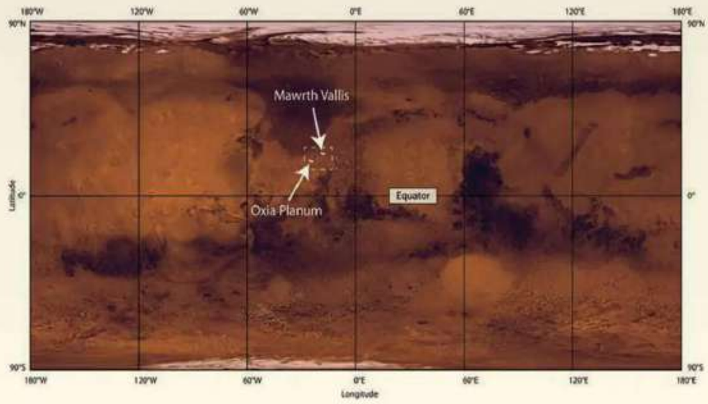
LANDING SITE: Oxia Planum, Mars

MISSION DURATION: 7 months on the surface

MISSION PURPOSE:
To explore an ancient environment that was once water-rich and that could have been colonised by primitive life

ESA

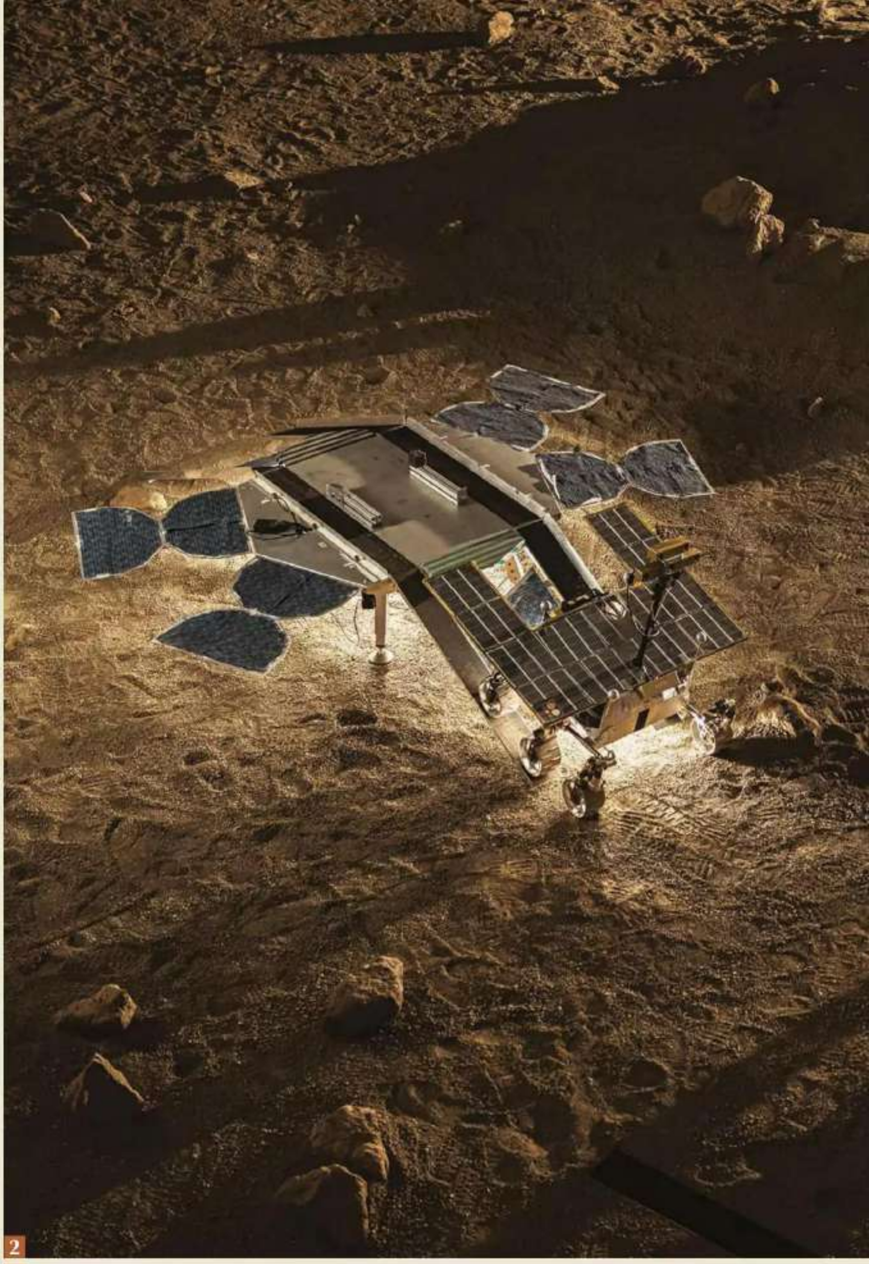




THE LANDING SITE

Oxia Planum – the preferred landing site – is rich in clays and minerals that have resulted from prolonged rock interactions with water, making it an ideal location to look for traces of biological activity in the sediment.

1



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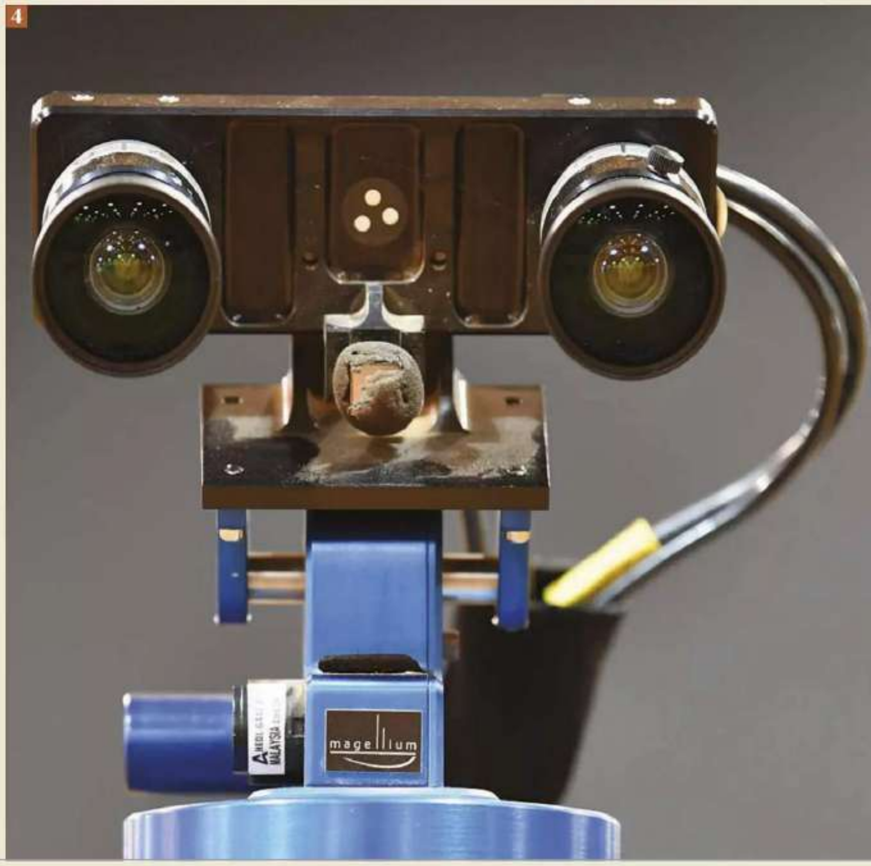


1. The Aerospace Logistics Technology Engineering Company (ALTEC) in Turin has a platform with a well that allows the operators to test the rover's drilling equipment. The rover will drill two metres down into the Martian surface to sample the soil, analyse its composition and search for evidence of past – and perhaps even present – life buried underground.

2. ALTEC has a Mars yard filled with 140 tonnes of rocks and soil, specially designed to mimic the surface of the Red Planet. This allows scientists to rehearse various scenarios prior to launch.

3. The ESA carrier module that will house the Rosalind Franklin rover on its journey from Earth to Mars is under construction here. It will also provide the communication link between Earth and the spacecraft during the trip.

4. The two cameras mounted on top of the Rosalind Franklin rover allow it to 'see' in 3D. It will use the cameras to analyse the slopes and the rocks ahead of it to make sure it doesn't get stuck.

5. All of the components of the rover are sterilised before they are assembled in a purpose-built clean room. This ensures that dirt or microbes from Earth will not contaminate any evidence of life on Mars.

6. The rover is scheduled for launch in July 2020. It will then embark on an eight-month interplanetary cruise before landing on the surface of the Red Planet.

3

5

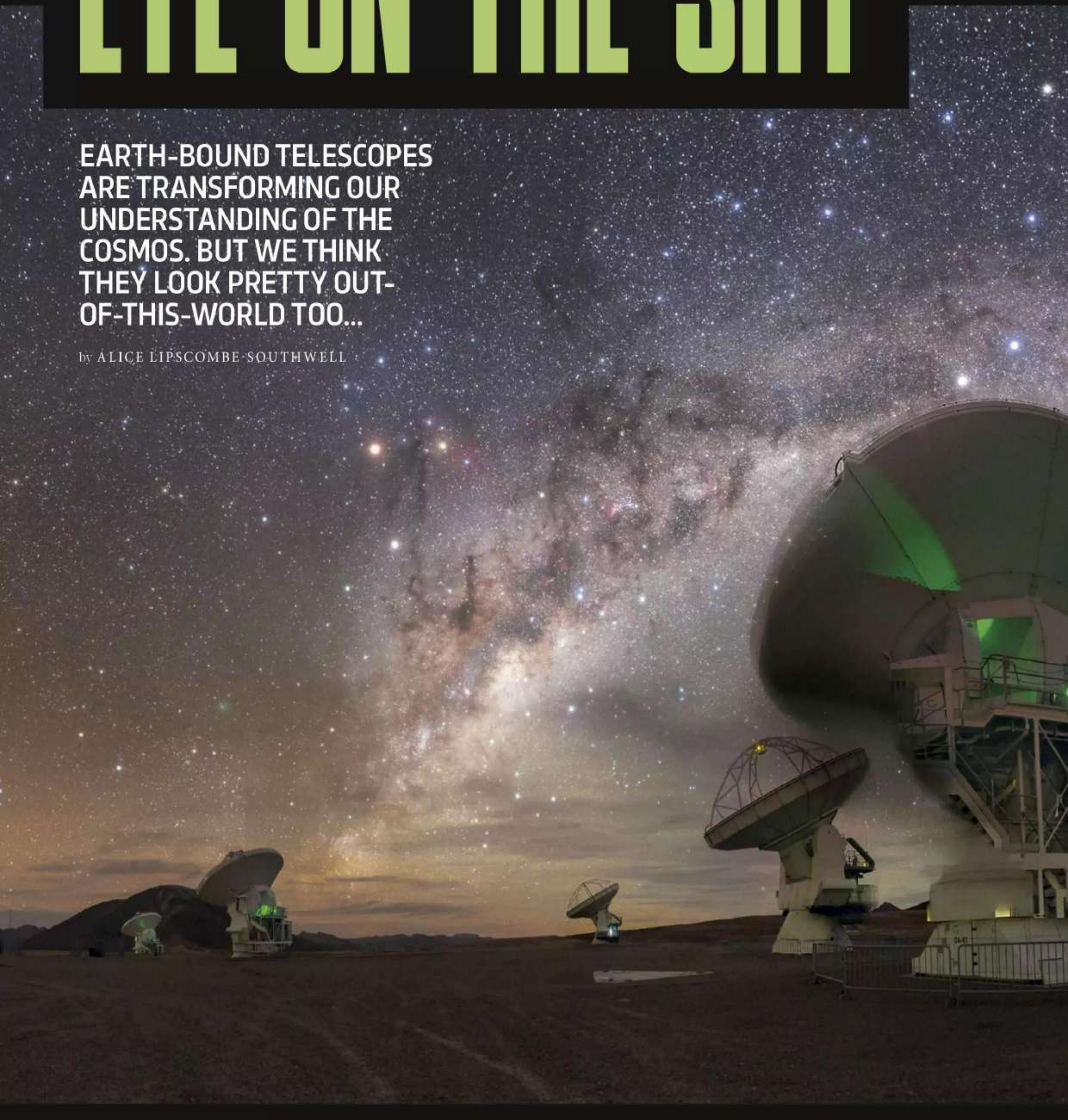
6

ESA X4, GETTY IMAGES

EYE ON THE SKY

EARTH-BOUND TELESCOPES ARE TRANSFORMING OUR UNDERSTANDING OF THE COSMOS. BUT WE THINK THEY LOOK PRETTY OUT-OF-THIS-WORLD TOO...

by ALICE LIPSCOMBE-SOUTHWELL



PEEK INTO THE PAST

ATACAMA LARGE MILLIMETER/ SUBMILLIMETER ARRAY (ALMA)

Chajnantor plateau, Atacama Desert, ***Chile***

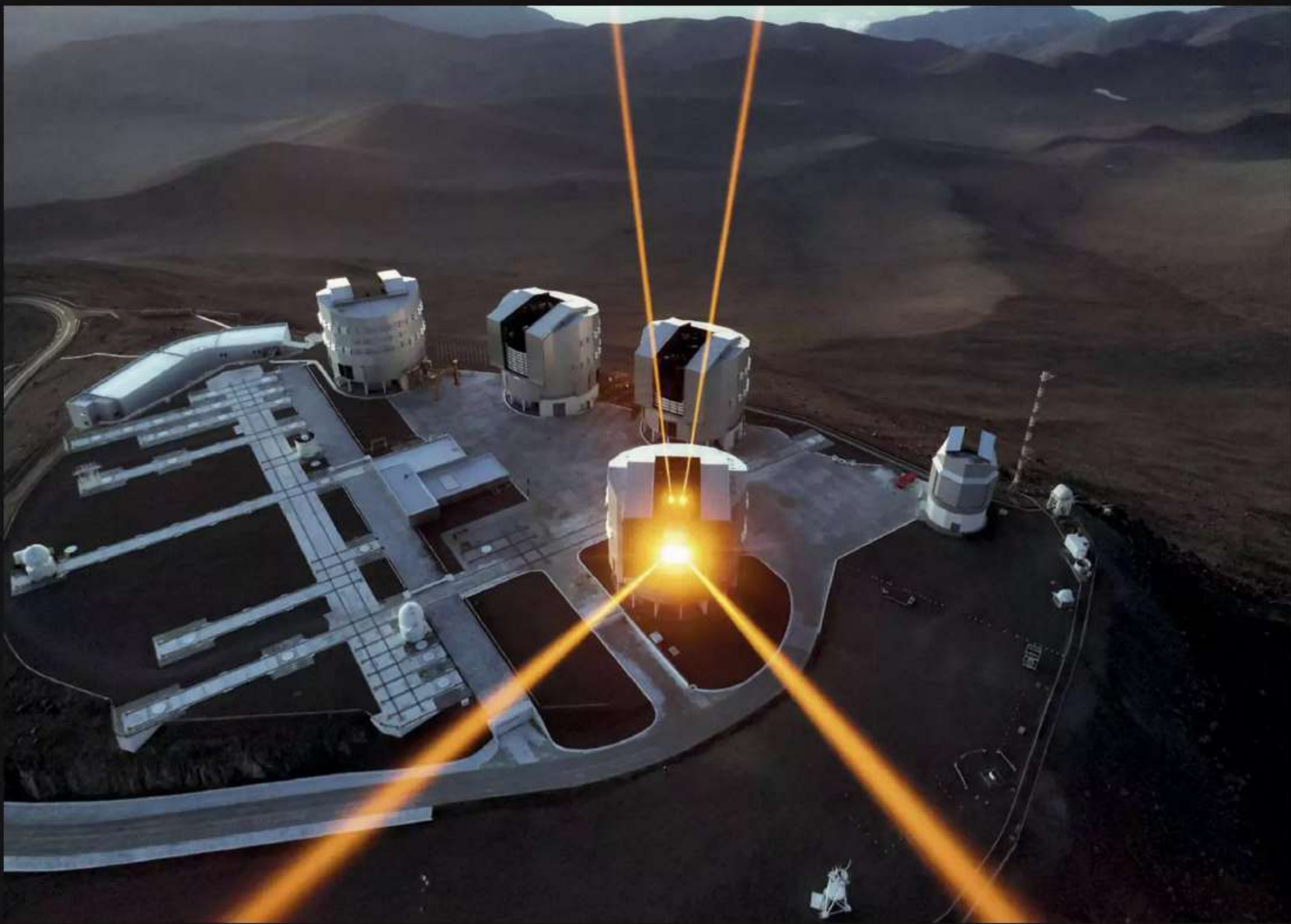
ALMA

The Atacama Desert in Chile is an astronomer's paradise. Thanks to its high altitude, cold nights, scant precipitation and lack of pollution, it boasts some of the clearest night skies on the planet. That's why the European Southern Observatory (ESO) – an astronomical research organisation of 16 countries – worked with Chile to set up powerful ground-based telescopes in the desert, including the Atacama Large Millimeter/submillimeter Array (ALMA).

Beginning observations in 2011, the high-tech telescope consists of 66 precise antennas that can be arranged in different ways to give a variable zoom, capturing sharper detail than the Hubble Space Telescope. ALMA studies light with wavelengths of around a millimetre, originating from the Universe's coldest objects that exist at temperatures at just above absolute zero. These objects include the molecular gas and dust clouds that are the building blocks of galaxies, stars and planets. By studying these regions of the Universe, scientists will be able to decipher the mysteries of planetary formations as well as our cosmic origins.

P HORÁLEK/ESO

The lasers seen here act as an artificial 'guide star', which allows the telescope to compensate for turbulence in the Earth's atmosphere to obtain clearer images



DECIPHER THE UNIVERSE

VERY LARGE TELESCOPE (VLT)

Cerro Paranal, Atacama Desert, ***Chile***

Around 500 kilometres away on the other side of the desert on Cerro Paranal is the Very Large Telescope (VLT). It consists of four 'unit telescopes' each named after a celestial object in the Mapuche language – spoken by the indigenous population to south-central Chile – and complemented by four moveable 'auxiliary telescopes'. Just one of the unit telescopes can see objects four billion times fainter than is visible with the human eye. Alternatively, the telescopes can work together to form a huge 'interferometer', allowing astronomers to view much finer detail than is possible by using each telescope individually.

The VLT first started operations in 1998 and has transformed our understanding of the Universe, with its results leading to an average of more than one peer-reviewed paper every day. Some of its most iconic work includes testing Einstein's General Relativity by tracking the movement of a star passing through the gravitational field around the Milky Way's supermassive black hole. However, it has also calculated the age of ancient stars in the NGC 6397 cluster, and has analysed the atmosphere of a super-Earth exoplanet, helping scientists to learn more about worlds beyond our Solar System. The VLT was even able to detect carbon monoxide molecules in a galaxy almost 11 billion light-years away.

G HUDEPOHL/ESO, V FORCHI/ESO X2

The Five-hundred-meter Aperture Spherical Telescope (FAST) is the world's largest single-dish radio telescope

GETTY IMAGES

WHAT A DISH!

FIVE-HUNDRED-METER APERTURE SPHERICAL TELESCOPE (FAST)

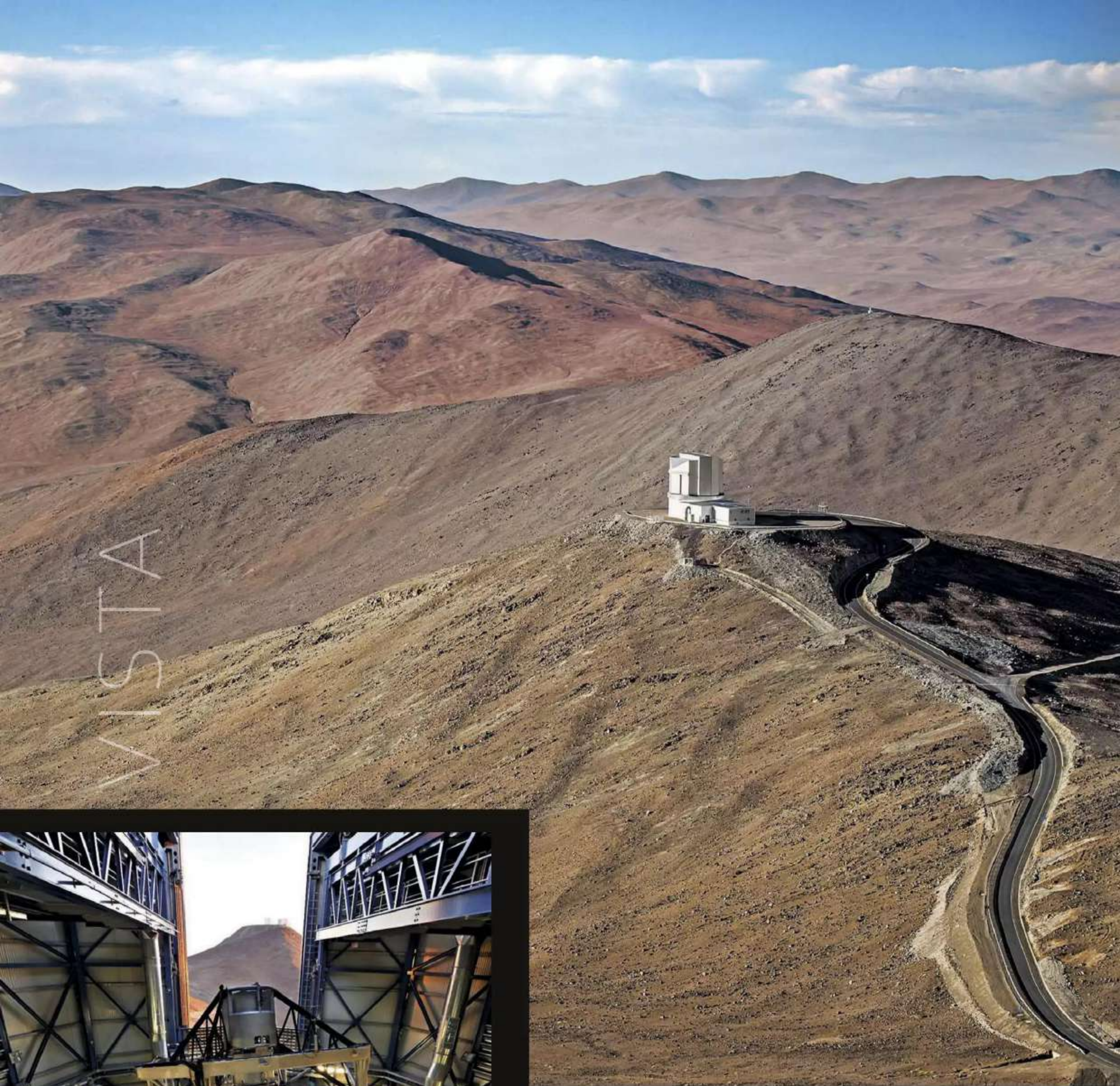
Pingtang County, Guizhou, ***China***

On the other side of the world in China's remote and mountainous Pingtang County lies the newest telescope in our roundup, the Five-hundred-meter Aperture Spherical Telescope (FAST). This radio telescope started formal operations in January 2020, and consists of an enormous 500m-diameter dish composed of 4,450 triangular metal panels that can be adjusted to target different areas of the sky. The dish focuses incoming radio waves onto a receiving antenna.

It first opened to astronomers in autumn 2019 and is designed to search the skies for pulsars, fast radio bursts (FRBs), and potentially alien life. Pulsars were first spotted by Jocelyn Bell Burnell and Antony Hewish back in the 1960s and were initially dubbed LGMs for 'Little Green Men', until they were identified as highly magnetised, rapidly rotating neutron stars that can only be detected by radio telescopes. FRBs were discovered back in 2007, and are brief, energetic bursts of radio emissions that take place all over the cosmos, however, their precise cause has not yet been identified.

FAST

ALAMY X3, G HUDEPOHL/ESO, A TUDORICA/ESO



MAKE THE INVISIBLE VISIBLE

VISIBLE AND INFRARED SURVEY TELESCOPE FOR ASTRONOMY (VISTA)

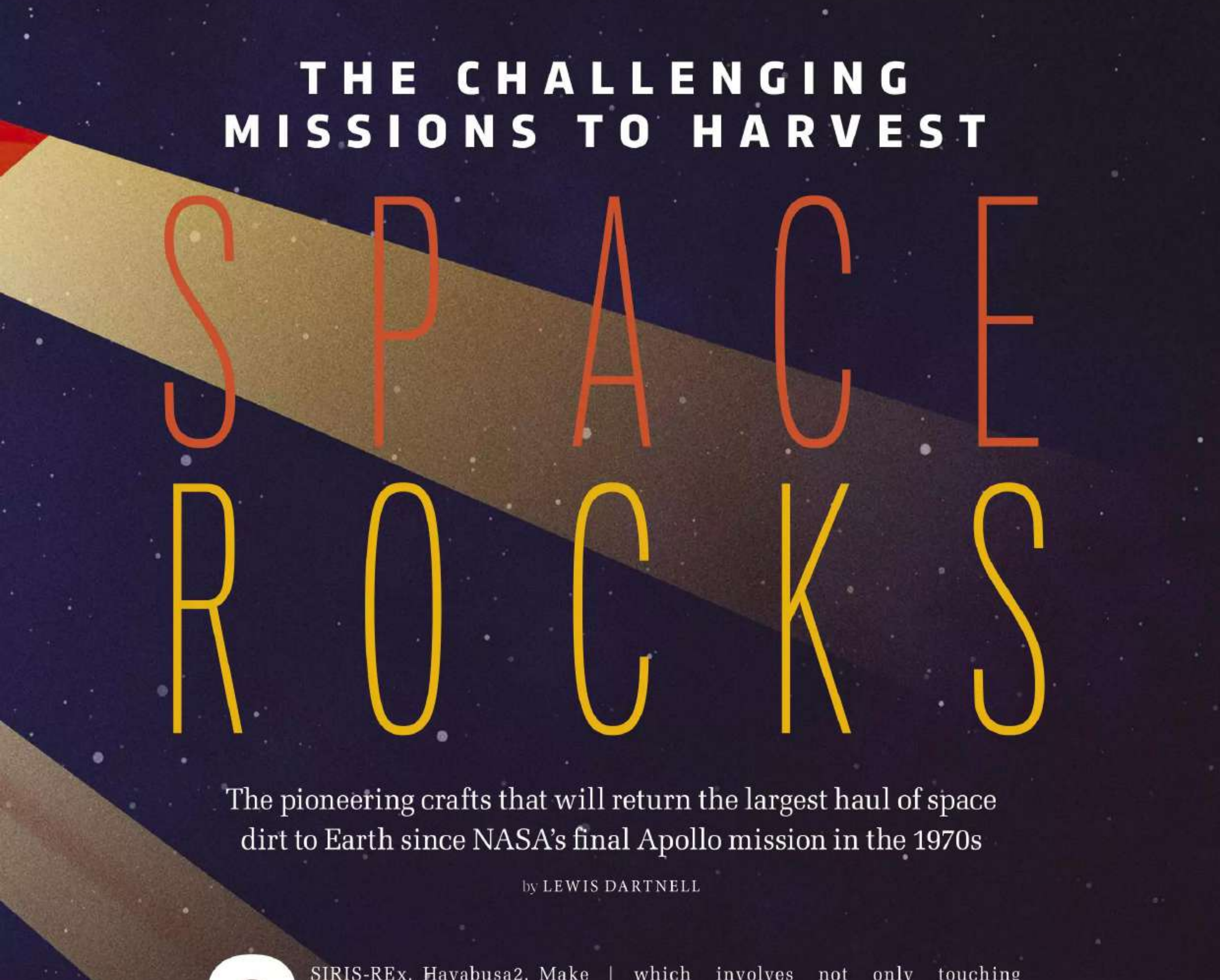
Cerro Paranal, Atacama Desert, ***Chile***

At the same site as the VLT is the Visible and Infrared Survey Telescope for Astronomy (VISTA), operating since 2009. Also owned by ESO, this telescope is equipped with a sensitive near-infrared camera that can see things that are invisible to the human eye. This means that it can look for substellar bodies such as brown dwarfs, which are incredibly faint in terms of visible wavelengths, as well as distant objects like quasars and other galaxies. But it can also peer through the clouds of dust that obscure swathes of the cosmos, allowing it to glimpse many of the individual stars at the centre of the Milky Way. This will enable scientists to map our Galaxy in much greater detail.

Some of the most incredible images taken by VISTA so far include stunning views of the Flame Nebula, the Orion Nebula and the Lagoon Nebula, all located thousands of light-years away. **SF**

by **ALICE LIPSCOMBE-SOUTHWELL**
Alice is the managing editor for BBC Science Focus *and* BBC Science Focus Collection.

Listen to an episode of *In Our Time* about asteroids **bit.ly/melvyn_bragg**



THE CHALLENGING MISSIONS TO HARVEST SPACE ROCKS

The pioneering crafts that will return the largest haul of space dirt to Earth since NASA's final Apollo mission in the 1970s

by LEWIS DARTNELL

OSIRIS-REx. Hayabusa2. Make a note of these two names: you're going to be hearing a lot about them over the coming months. These spacecraft – one operated by NASA and the other by the Japan Aerospace Exploration Agency, JAXA – have each been orbiting round their own target asteroid. They promise to teach us a great deal about the origins of the Solar System, how we might deflect an asteroid on a collision course with the Earth, and even the molecular origins of earthly life.

Both NASA's OSIRIS-REx and JAXA's Hayabusa2 are sample-return missions, which involves not only touching gently onto their asteroid's surface to collect a scoop of its ancient material, but then returning it safely back to eagerly waiting scientists on Earth. This sort of return trip mission within deep space is fabulously complex, and both probes are marvels of engineering. The Japanese probe is a follow-up to their earlier asteroid mission, Hayabusa, which returned a small sample from the asteroid Itokawa in 2010. Despite suffering numerous glitches, Hayabusa racked up a string of accomplishments, including being the first spacecraft designed to land and take off from an asteroid and

ILLUSTRATION: MAGIC TORCH

the first to return an asteroid sample to Earth. Now on its way home after what is hoped to be a successful mission, Hayabusa2 uses the same basic spacecraft structure as its predecessor, but incorporates more backup systems to improve reliability, along with some technological advances. As well as upgrades to the communication antenna and guidance systems, Hayabusa2's ion engines are 25 per cent more powerful than its predecessor's, and the probe was able to autonomously control its own final descent to the remote asteroid's surface. Hayabusa2 was also like a mothership in its own right – prior to sampling it deployed a small lander and three rovers onto the asteroid's surface for a closer look, which were able to hop around the landscape to different locations.

"These space rocks are thought to have delivered a lot of water to primordial Earth"

Meanwhile, NASA's OSIRIS-REx is the first ever US asteroid sample-return mission. This spacecraft is about twice the size of Hayabusa2 and, rather than using ion engines, it was able to fire standard rocket thrusters to accelerate on its trajectory to its target asteroid, where it is currently in orbit. Both missions have been able to complete a survey of their target asteroids, which included mapping the surfaces and remotely detecting minerals using spectroscopy. Scientists were able to use these results to determine the best spot on their asteroids for Hayabusa2 and OSIRIS-REx to descend to collect their samples.

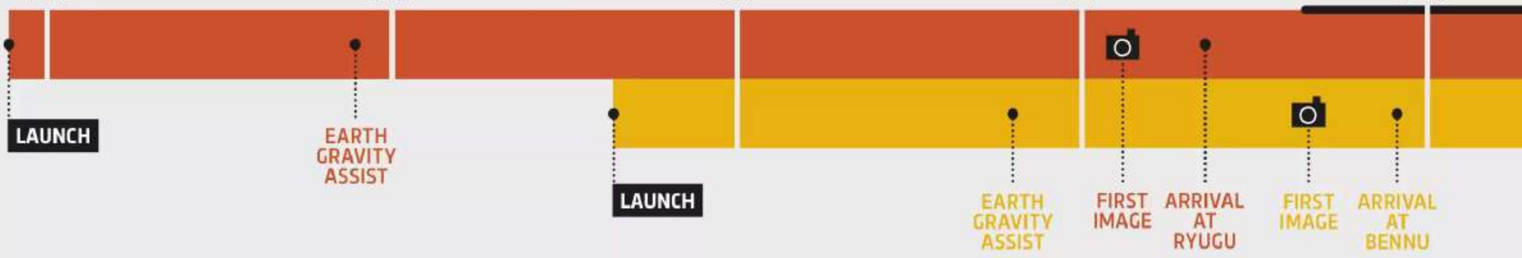
TIME CAPSULES

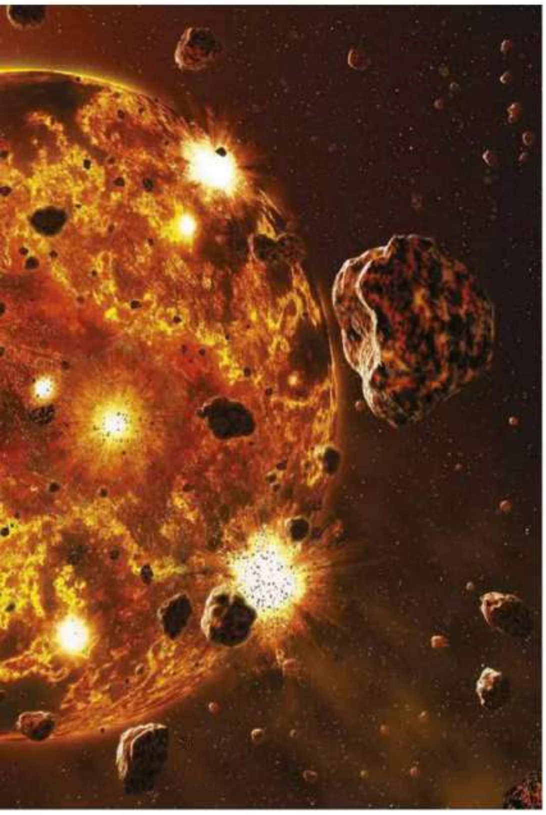
Asteroids are important to study because they represent primordial material left over from the formation of the planets. They are like time capsules from before the creation of the Earth, preserving matter since the beginning of the Solar System. By studying them up-close, scientists hope to be able to answer some pretty fundamental questions about the formation and development of the Solar System. Specifically, it will help us to understand how planets like the Earth were born, by allowing us to observe the material from which rocky planets form.

Even more excitingly, both the target asteroids for OSIRIS-REx and Hayabusa2 are carbonaceous asteroids. These kind of space rocks have a high percentage of carbon compounds as well as water-containing minerals, and are thought to have delivered a lot of water to the primordial Earth to fill our oceans, along with organic chemicals like amino acids. As Dr Yuichi Tsuda, project manager for Hayabusa2, puts it, "The primary reason we chose our target asteroid is that it is a C-type [carbon-rich]. Telescope observations suggest that it should contain lots of carbon as well as water-related minerals, and so give us important clues as to how life on Earth became possible. We've never explored or sampled this type of asteroid before, so these missions are really exciting."

SCIENCE PHOTO LIBRARY, GETTY, JAXA, ILLUSTRATION: PHIL ELLIS

Hayabusa2 & OSIRIS-REx OPERATIONS TIMELINE





ABOVE
Asteroids are time capsules from the Solar System's formation

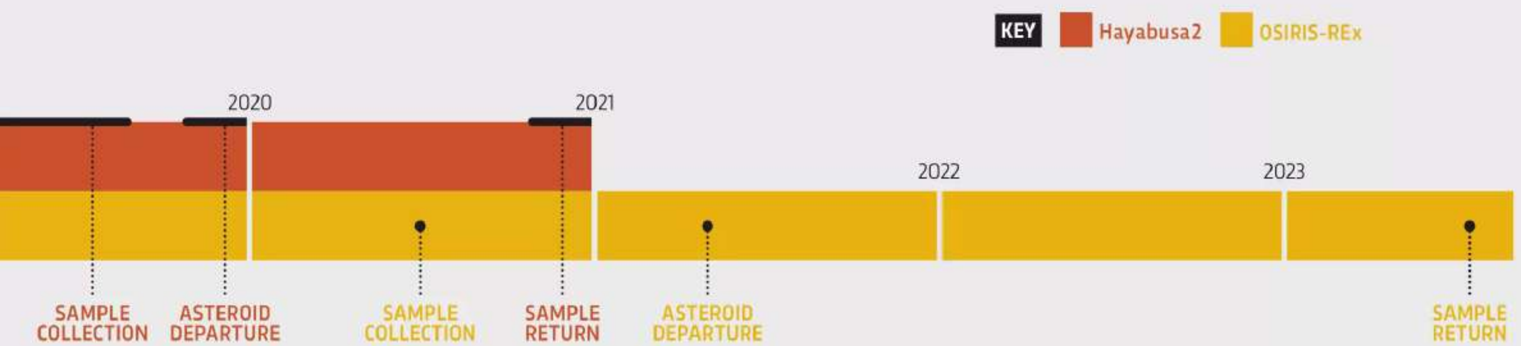
CENTRE TOP
A recent image of asteroid Ryugu from Hayabusa2

CENTRE BOTTOM
Extracting samples from the first Hayabusa mission upon its return to Earth

RIGHT
OSIRIS-REx being assembled prior to its launch in 2016

Organic chemistry forms the building blocks of all life on Earth. Cells of organisms are made up of certain molecules joined together into long chains: amino acids that build our proteins; nucleotide bases that make DNA and RNA; and the long, oily chains that make up the outer membranes of cells. We know that many of these chemical building blocks are formed in the cosmos – through what is known as 'astrochemistry'– in the cold gas clouds floating through space, as well as the warmer regions around old, dying stars. When this material pulls together under gravity as a new solar system forms, the organic molecules become incorporated into asteroids and comets. So while asteroids don't deliver fully-formed cells to young planets, they may have provided many building blocks for the origin of life – and finding organic molecules on these asteroids would offer support for this idea.

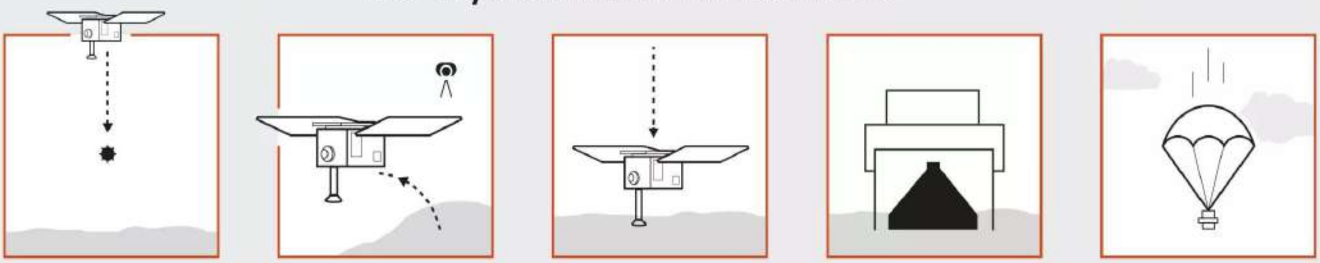
Organic molecules like amino acids have previously been found in meteorites that have landed on the Earth, but these missions will be the first time that scientists will be able to get their hands on carbonaceous material directly from an asteroid. Although meteorites naturally deliver us lumps of primordial space rock, as soon as they land they're susceptible to contamination from Earth's environment. Hence, sample-return missions are important to researchers – material is collected from the source and hurried back via a robotic courier. Prof Sara Russell is a planetary scientist at London's Natural History Museum, and will run some of the preliminary studies on the material returned by OSIRIS-REx. "I've worked



Hayabusa2

Launch mass: 600kg
Size: 1 x 1.6 x 1.3m
Target asteroid: 162173 Ryugu
Launch: 3 December 2014, Tanegashima Space Centre, Japan
Sample size to be collected: Up to 300mg
Sample return: December 2020
Power: Two solar arrays, generating between 1.4kW and 2.6kW
Propulsion: Four ion engines and 12 rocket engines
Fuel: Xenon and hydrazine
Estimated cost: ¥16.4bn (£112m approx)

HOW Hayabusa2 COLLECTED ITS SAMPLES



1. The probe approached asteroid Ryugu, deploying its impactor at an altitude of 500m. After detonation, this fired a 2.5kg copper projectile into the asteroid's surface, blasting out a 2m-wide crater.
2. Before detonation, the probe deployed a camera into space to watch the explosion, and escaped to the far side of the asteroid in order to protect itself.
3. Once safe, Hayabusa2 returned to the crater site and used its rocket thrusters to descend, until its extendable 'sampler horn' was able to touch the surface.
4. The sampler horn then fired out a metal projectile, collecting the resulting debris in the re-entry capsule.
5. The capsule parts from its mothership on return to Earth, parachuting into the RAAF Woomera Range Complex in South Australia. Hayabusa2 moves into an orbit around the Sun.

on meteorites my whole career, but we're never really sure what sort of asteroid, or where in the Solar System they've come from," she explains. "OSIRIS-REx is like going on a grand field trip to pick our own sample, and when it comes back to Earth in 2023 it will be a meteoriticist's dream come true!"

Both NASA and JAXA chose their target asteroids because they offer pristine carbonaceous material for researchers to study. But they also needed asteroids that are roughly the right size (with enough gravity for their probes to orbit), that aren't spinning too quickly (so that the probes can 'touch down' safely), and that are in a near-Earth orbit that the probes can actually reach. "Asteroids that fit all these criteria are actually quite rare," says Prof Hitoshi Kuninaka, who has been leading the development of Hayabusa2's ion engines. NASA's OSIRIS-REx is orbiting asteroid 101955 Bennu, whereas the JAXA scientists picked asteroid 162173 Ryugu for their mission. And NASA will collect their samples in a spectacularly audacious way.

OSIRIS-REx will slowly lower itself towards the asteroid's surface, without actually landing, and fold its solar panels upwards to protect them. Here, it will extend a robotic arm and puff a sharp burst of nitrogen gas to blow up particles into its collection head. After just five seconds, the sample collector will close and OSIRIS-REx will automatically begin to back away from the surface. With anything between 60g and 2kg gathered, this precious cargo will be sealed into a re-entry capsule and fired back towards the Earth, where it'll parachute safely to the ground in Utah to be picked up.

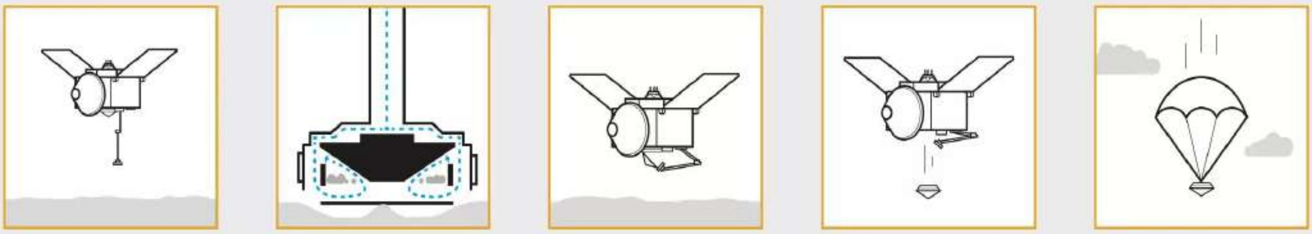
Hayabusa2 was even more innovative when it collected its samples in 2019. It carried a device called the Small Carry-on Impactor (SCI), consisting of a 2.5kg copper projectile and a shaped

ILLUSTRATION: PHIL ELLIS

OSIRIS-REx

Launch mass: 2,110kg
Size: 2.43 x 2.43 x 3.15m
Target asteroid: 101955 Bennu
Launch: 8 September 2016, Cape Canaveral Air Force Station, Florida, USA
Sample size to be collected: Between 60g and 2kg
Sample return: September 2023
Power: Two solar arrays, generating between 1.2kW and 3kW
Propulsion: 28 rocket engines
Fuel: Hydrazine
Estimated cost: $800m (£614m approx)

HOW OSIRIS-REx WILL COLLECT ITS SAMPLES



1. The probe approaches the surface of asteroid Bennu, delicately positioning itself above the asteroid (without landing) using a pair of specialised low-thrust rocket engines.
2. OSIRIS-REx briefly touches the asteroid with its 3m-long robotic arm, using a puff of nitrogen to blow loose rock and dust into the collection head at the end of the arm.
3. The collection head is then stowed inside the Sample Return Capsule (SRC), ready for the journey home.
4. As OSIRIS-REx nears Earth, it releases the SRC, manoeuvres away and enters an orbit around the Sun.
5. The SRC parachutes into the Utah desert, complete with sample.

charge of plastic explosive. This explosive fired the copper impactor into Ryugu's surface at over 7,000km/h, blasting out a crater while Hayabusa2 flew around the far side of the asteroid to protect itself from the flying shrapnel. A camera released by the probe watched the impact, transmitting the images to Hayabusa2 before the probe returned to the crater to collect its sample. This enabled Hayabusa2 to analyse the interior structure of the asteroid, and gather material untouched by ultraviolet radiation and the solar wind.

Beyond teaching us about the origins of the Earth and the conditions for life, the probes have another critical aim: to help prevent a cataclysmic cosmic collision. As Bennu and Ryugu orbit the Sun close to the Earth, they are exactly the sort of asteroids that present a potential hazard to our planet. The orbit of Bennu, for example, brings it close to the Earth every six years, and it's been calculated that there's a 1 in 1,410 chance that it might hit us between the years 2169 and 2199.

OSIRIS-REx will help us understand how the orbit of asteroids like Bennu might change over time through a process known as the Yarkovsky effect. This is a tiny force caused by the emission of infrared radiation from the Sun-warmed surface of an asteroid, but over long periods it can significantly nudge an object's orbit. OSIRIS-REx is studying this effect and what it means for the probability of Bennu impacting the Earth in the future. The probe is also measuring the asteroid's physical properties. Is it a single body, or perhaps composed of multiple boulders held together only loosely? We'd need to know this before deciding the best deflection technique.

These missions are spectacular both for their audacity, and sheer breadth of their vision. From the origins of life to protecting the life that now clings to survival, the probes promise to offer new insights into our place in the cosmos. **SF**

by **PROF LEWIS DARTNELL**
Lewis is an astrobiology researcher at the University of Westminster. His latest book Origins: How The Earth Made Us *(£9.99 Vintage), is out now.*

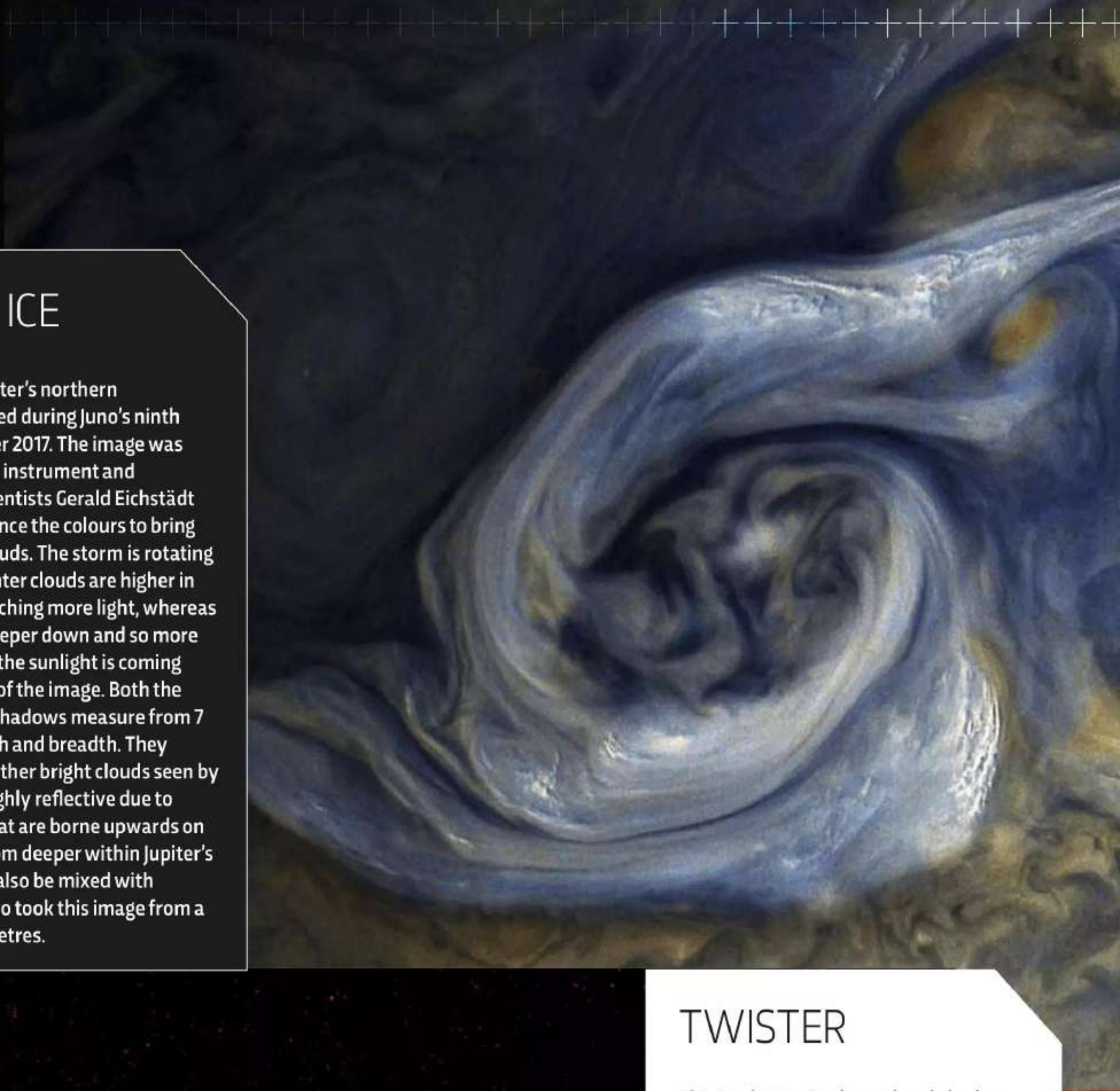
Enhanced colour image of Jupiter's Great Red Spot, a mega storm that's been swirling since at least the 19th Century

THANKS FOR ALL THE PICS

IN JULY 2018, JUNO WAS SCHEDULED TO END ITS MISSION TO STUDY JUPITER. BUT IN JUNE THAT YEAR, IT WAS ANNOUNCED THAT THE MISSION WOULD CONTINUE TO AT LEAST 2021. HERE, WE LOOK BACK OVER SOME OF JUNO'S INCREDIBLE PHOTOS THAT HAVE TRANSFORMED OUR UNDERSTANDING OF THE SOLAR SYSTEM'S BIGGEST PLANET

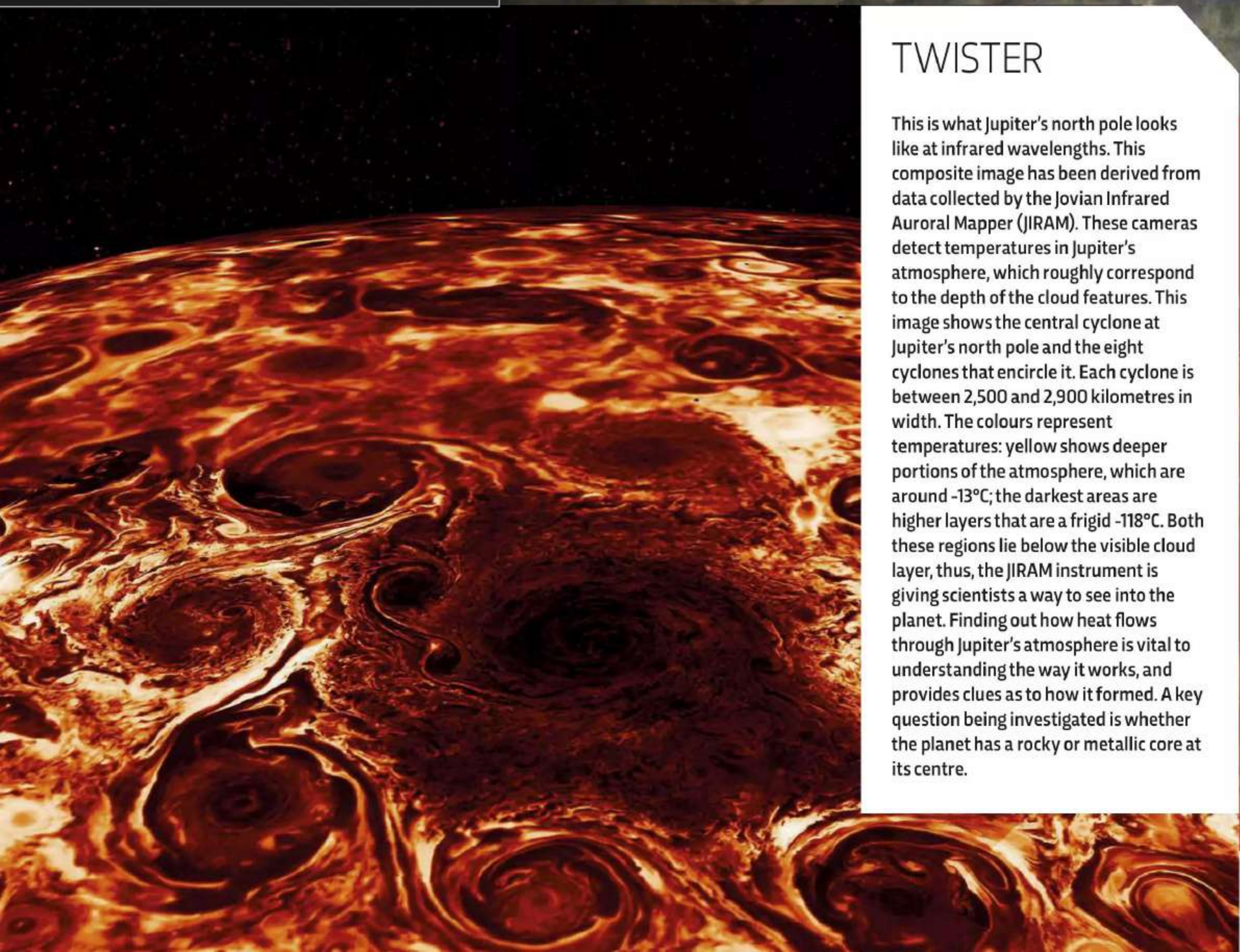
by DR STUART CLARK
Images NASA/JPL

In classical mythology, the god Jupiter surrounded himself in clouds to keep his antics hidden from view. Only his wife, Juno, could see through the veil to his true nature. And so it is with the NASA spacecraft of the same name. The secrets of the formation of the whole Solar System lie below Jupiter's all-encompassing clouds, just waiting to be discovered. Theories about our Solar System formation all begin with the collapse of a giant cloud of gas and dust, otherwise known as a nebula, the majority of which formed the Sun. Like the Sun, Jupiter is mostly hydrogen and helium, so it too must have formed early on, capturing most of the leftover material after our star formed. How this happened, however, is unclear. Did a massive planetary core form first and gravitationally capture all that gas, or did an unstable region collapse inside the nebula, triggering the planet's formation? Once processed, the data taken by Juno's instruments will give researchers insights on how the planet formed and what the conditions in the early Solar System were like. But it also carries an instrument called JunoCam, which has taken a raft of images that so-called citizen scientists from the general public can process, and submit back to NASA. The results have been spectacular.



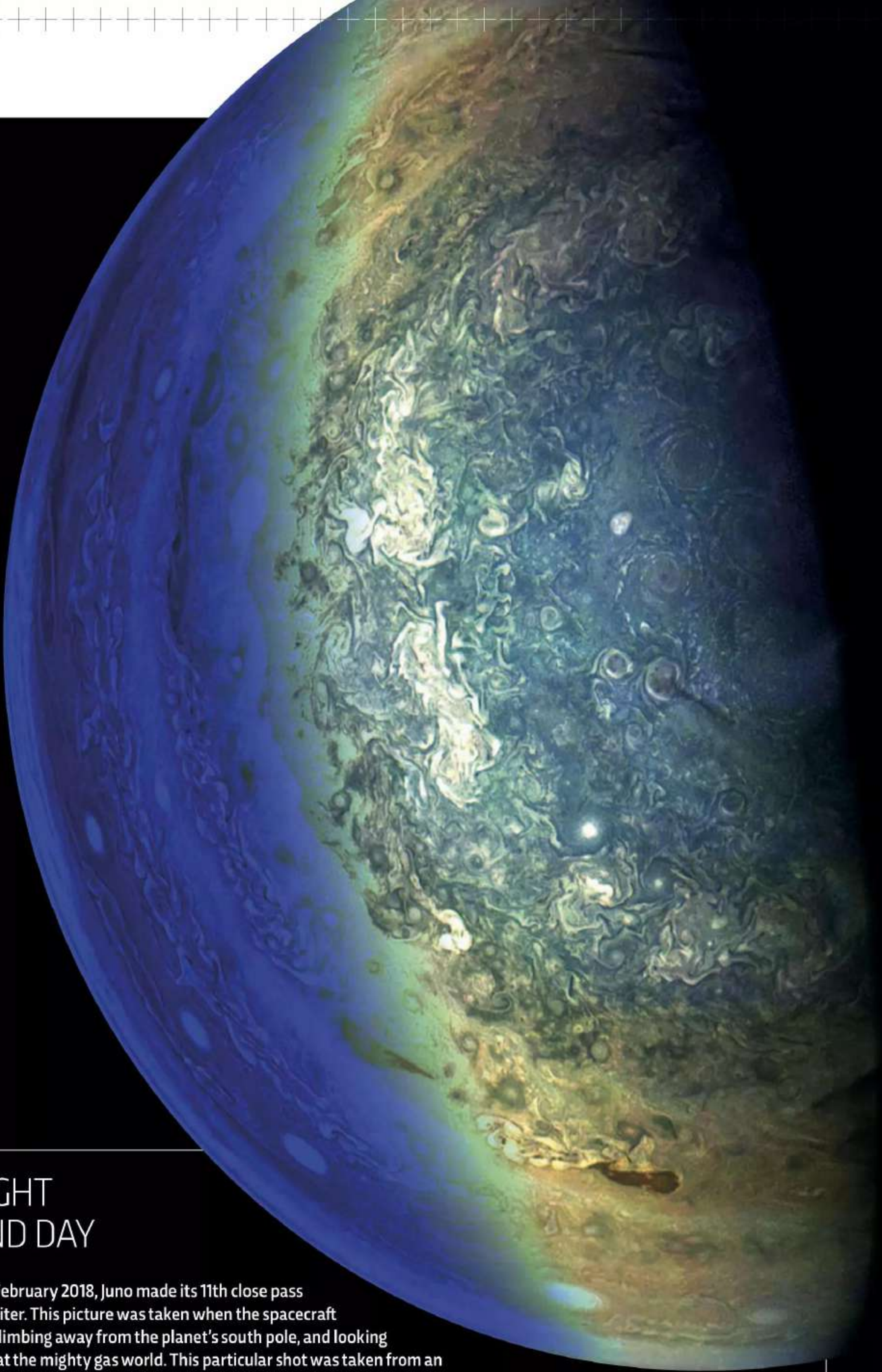
CLOUDS OF ICE

This raging storm in Jupiter's northern hemisphere was captured during Juno's ninth close flyby on 24 October 2017. The image was taken with the JunoCam instrument and processed by citizen scientists Gerald Eichstädt and Seán Doran to enhance the colours to bring out the details in the clouds. The storm is rotating anticlockwise. The brighter clouds are higher in the atmosphere and catching more light, whereas the darker clouds are deeper down and so more shadowy. In this image, the sunlight is coming from the left-hand side of the image. Both the bright clouds and their shadows measure from 7 to 12 kilometres in length and breadth. They appear to be similar to other bright clouds seen by Juno, so are probably highly reflective due to ammonia ice crystals that are borne upwards on rising currents of gas from deeper within Jupiter's atmosphere. They may also be mixed with crystals of water ice. Juno took this image from a distance of 10,108 kilometres.



TWISTER

This is what Jupiter's north pole looks like at infrared wavelengths. This composite image has been derived from data collected by the Jovian Infrared Auroral Mapper (JIRAM). These cameras detect temperatures in Jupiter's atmosphere, which roughly correspond to the depth of the cloud features. This image shows the central cyclone at Jupiter's north pole and the eight cyclones that encircle it. Each cyclone is between 2,500 and 2,900 kilometres in width. The colours represent temperatures: yellow shows deeper portions of the atmosphere, which are around -13°C; the darkest areas are higher layers that are a frigid -118°C. Both these regions lie below the visible cloud layer, thus, the JIRAM instrument is giving scientists a way to see into the planet. Finding out how heat flows through Jupiter's atmosphere is vital to understanding the way it works, and provides clues as to how it formed. A key question being investigated is whether the planet has a rocky or metallic core at its centre.

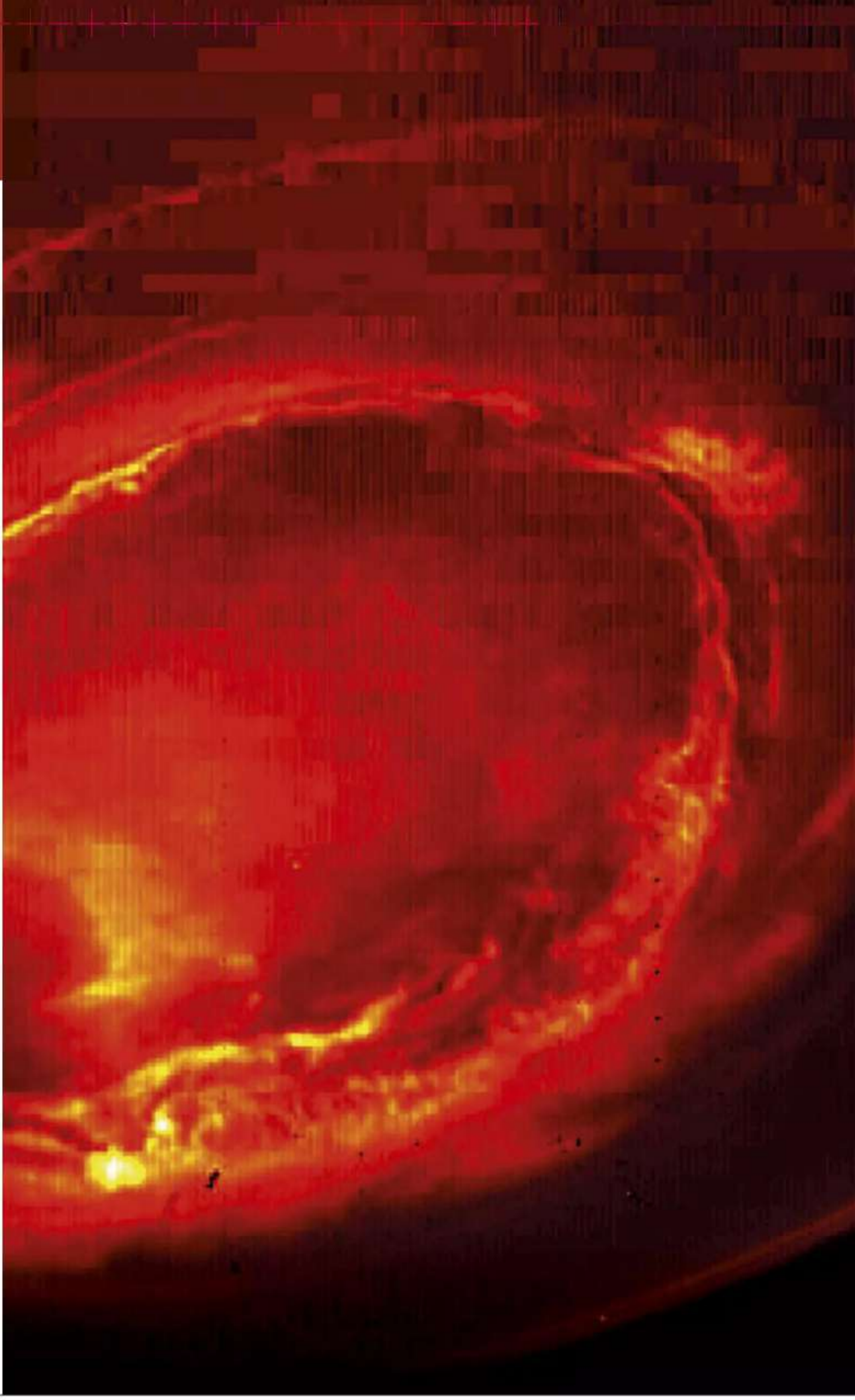


NIGHT AND DAY

On 7 February 2018, Juno made its 11th close pass of Jupiter. This picture was taken when the spacecraft was climbing away from the planet's south pole, and looking back at the mighty gas world. This particular shot was taken from an altitude of 120,533 kilometres when the spacecraft was almost directly over the planet's south pole. The colour has been enhanced over what would be seen with the naked eye. The line separating the dayside of the planet from the nightside is called the 'terminator'. To capture details in this 'twilight zone', when day is turning to night and vice-versa, the JunoCam instrument took a number of different images with different exposure times. The longer exposures showed the details of the twilight zone but overexposed the daylight side of the planet. The shorter exposures captured the bright hemisphere but failed to show anything near the terminator. Computer processing by citizen scientist Gerald Eichstädt then merged the two images.

EYES OF THE STORM

Although the Great Red Spot grabs the glory when we think about Jupiter's giant storms, it is just one of many that rage in the planet's atmosphere. This image shows two white storms. It was taken by the JunoCam instrument from an altitude of 33,115 kilometres during the ninth flyby of Jupiter on 24 October 2017, and was processed by Gerald Eichstädt and Seán Doran. The image is more colourful than our eyes would see because it has been enhanced to bring out the details in the atmosphere. The storm at the bottom of the image is part of Jupiter's 'String of Pearls'. This is a series of oval storms, all of them white in colour, that encircle the planet's southern hemisphere at a latitude of 40°. Since 1986, the number of storms has varied from six to nine. There are currently eight of these storms, all rotating in an anticlockwise direction. These vast storms are being powered by heat that is generated in Jupiter's interior.



JUNO MISSION

9 JUNE 2005
NASA selects Juno to become the space agency's next New Frontiers mission.

5 AUGUST 2011
Juno launches at 16:25 GMT from Cape Canaveral Air Force Station atop an Atlas V rocket.

5 JULY 2016
Juno arrives at Jupiter and goes into a polar orbit that varies in altitude from four million to eight million kilometres.

27 AUGUST 2016
Juno completes its first Jupiter flyby. All systems and instruments are working well.

19 OCTOBER 2016
Juno is meant to perform an engine burn to reduce its orbit time from 53 to 14 days. Mission managers postpone and ultimately cancel this due to a glitch.

10 JULY 2017
During the seventh close flyby, Juno passes over Jupiter's most famous atmospheric feature, the Great Red Spot.

16 JULY 2018
Juno's nominal mission came to an end but the spacecraft was still healthy, so its operational life was extended.

30 JULY 2021
Juno will fire its thrusters to decrease its orbit so much that it burns up in Jupiter's atmosphere.

ALIEN AURORA

This infrared image gives an unprecedented view of the southern aurora of Jupiter. The view is a mosaic of three images taken minutes apart as the craft was pulling away from Jupiter, after its first close approach. From Earth, the planet's southern aurora can hardly be seen. It was captured by Juno's Jovian Infrared Auroral Mapper (JIRAM) on 27 August 2016. Auroras are ovals of light that occur when particles from the Sun strike molecules in a planet's atmosphere and cause them to glow. The auroras appear as ovals because the magnetic field of the planet corrals the solar particles into a cone-shaped funnel that feeds them into the atmosphere around the planet's magnetic poles. The same occurs at Earth, but as Jupiter's magnetic field is the strongest planetary field in the Solar System – fully 20,000 times stronger than Earth's – its auroras are stronger. This image is composed of wavelengths longer than visible light, ranging from 3.3 to 3.6 micrometres (one micrometre = one-thousandth of a millimetre). These wavelengths were chosen because they are the ones emitted by excited hydrogen ions. These are atoms that have lost an electron particle and dominate the planet's atmosphere.

THE JUNO CRAFT

1 JUNOCAM (hidden in this image)
Takes colour images

2 GRAVITY SCIENCE
Studies Jupiter's gravitational fields

3 SOLAR PANEL
Three of these power the craft

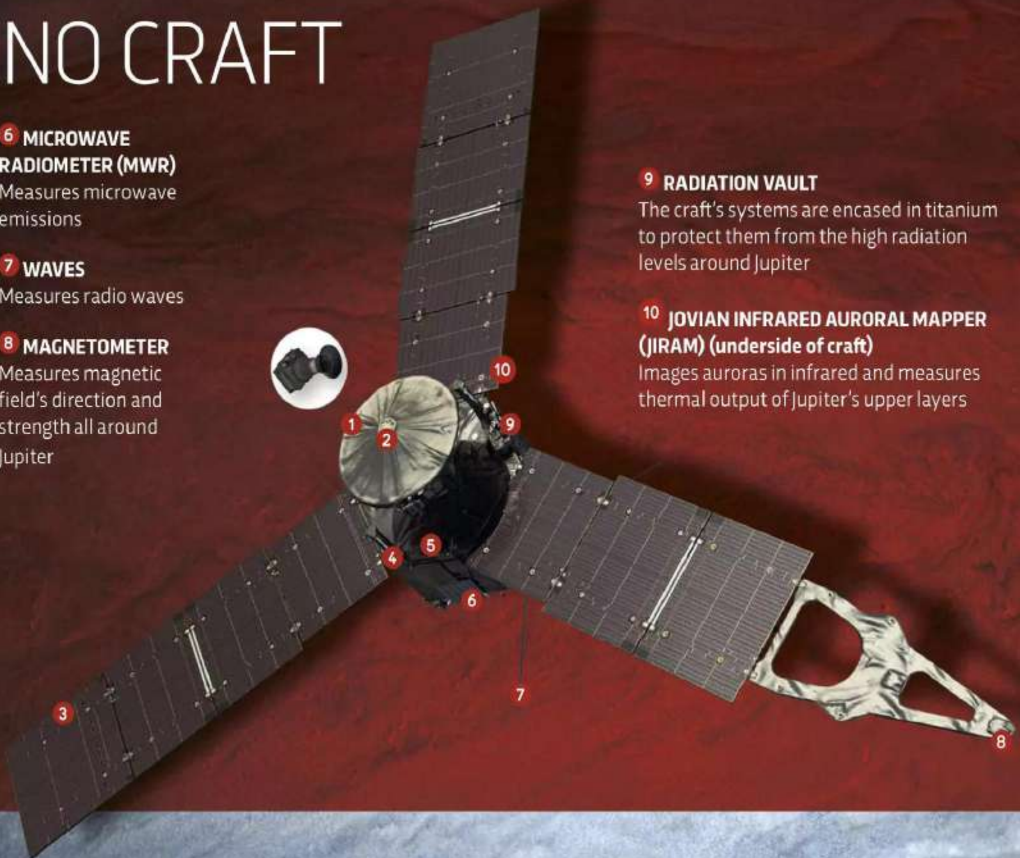
4 JOVIAN ENERGETIC PARTICLE DETECTOR INSTRUMENT (JEDI)
Detects highest energy particles

5 JOVIAN AURORAL DISTRIBUTION EXPERIMENT (JADE)
Detects particles and ions that cause the auroras

6 MICROWAVE RADIOMETER (MWR)
Measures microwave emissions

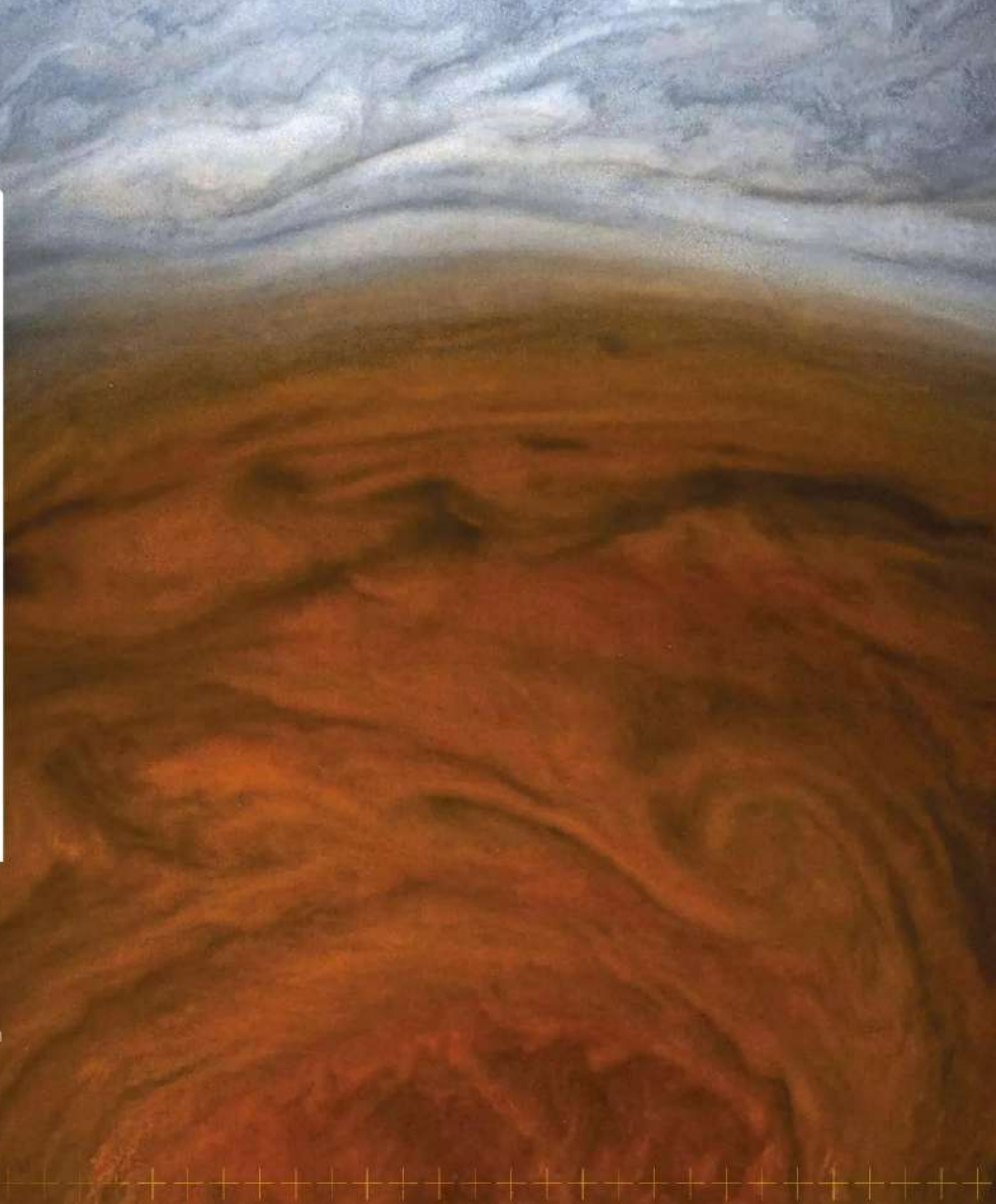
7 WAVES
Measures radio waves

8 MAGNETOMETER
Measures magnetic field's direction and strength all around Jupiter



9 RADIATION VAULT
The craft's systems are encased in titanium to protect them from the high radiation levels around Jupiter

10 JOVIAN INFRARED AURORAL MAPPER (JIRAM) (underside of craft)
Images auroras in infrared and measures thermal output of Jupiter's upper layers



ON THE SPOT

If you were to compose a list of the seven wonders of the Solar System, Jupiter's Great Red Spot would be near the top. This gigantic storm system is bigger than planet Earth, and rotates in an anticlockwise fashion with a period of about six days. Although a large circular storm has been reported on Jupiter from the 1660s onwards, it may not be the one we see today. Records are poor between 1713 and 1831 and may indicate that the original storm dissipated, and that the Great Red Spot we see today 'only' formed in the 19th Century. This image is an artistic endeavour based on real data. Citizen scientist Gerald Eichstädt used data from the JunoCam instrument and enhanced the colour to draw the eye into the storm. The raw image was taken on 10 July 2017, during Juno's 7th close flyby of the planet. When the image was taken, the craft was about 10,000 kilometres above the planet's cloud tops. SF

by **DR STUART CLARK** *(@DrStuClark)*
Stuart is an astronomy journalist with a PhD in astrophysics.

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NASA

Until now, illustrations like this offered the best idea of what Pluto looked like up close

PLUTO & BEYOND

After its landmark visit to Pluto, the New Horizons spacecraft continues to revolutionise our view of the outer Solar System

by DR ELIZABETH PEARSON

On 19 January 2006, a spacecraft raced up through the blue skies over Cape Canaveral. By the time it reached space, it was travelling at 16km/s, faster than any launch up until then. The spacecraft was New Horizons. Its destination was Pluto.

It had taken decades for the $700m (£532m approx) mission to come together. It would be another nine years before it finally reached its target, during which time the International Astronomy Union had demoted the world from 'planet' to 'dwarf planet'.

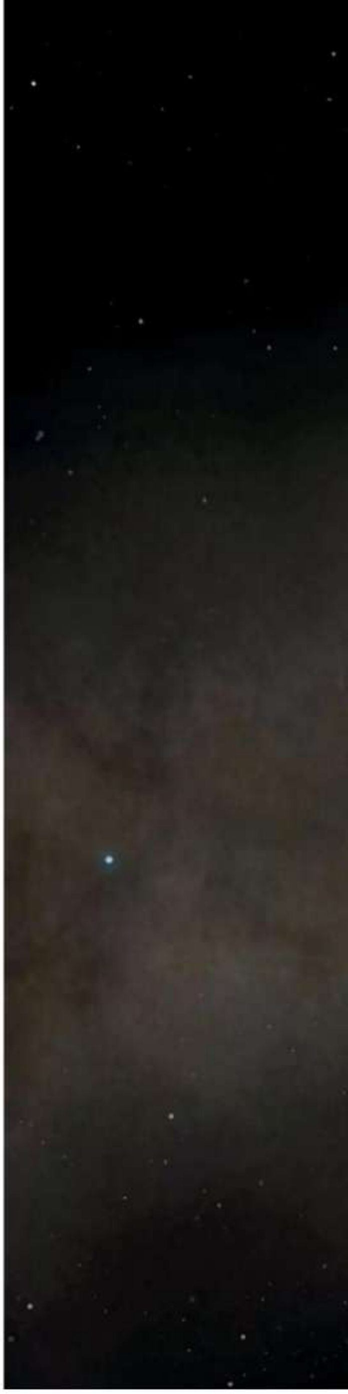
New Horizons eventually reached Pluto on 14 July 2015. The flyby lasted only a few hours, but in that time the spacecraft took 6.45GB of scientific readings of Pluto and its moons with its cameras, particle sniffers and dust detectors. While it only takes a few minutes to download a file that size to your home computer, transferring the data across the 4.8 billion kilometres between Pluto and Earth took a little longer – 16 months.

As the spacecraft was sending its trove of data, it continued racing outwards into the region of the Solar System that Pluto calls home – the Kuiper Belt, also known as the Kuiper-Edgeworth Belt.

"The Kuiper Belt is the third region of the Solar System as you move out," says Dr Alan Stern, the principal investigator of New Horizons.

The belt rings our Solar System between 20AU to 50AU (1AU is the distance between the Earth and Sun), and is filled with large icy bodies called Kuiper Belt Objects (KBOs). At 1,188km across, Pluto is one of the largest KBOs, but there are an estimated 35,000 space rocks floating through the region. They are thought to be the leftovers from when the planets formed and represent the most pristine example of the primordial nebula from which our Solar System was born. By studying these ice-rocks, planetary scientists hope to gain a better understanding of the conditions in which

ALAMY



"It is the first spacecraft to pass through these outer regions of our Solar System since the Voyager probes"

the planets grew.

Before the flyby of New Horizons, the only view we'd seen of these icy bodies were comets, many of which are thought to have originated in the Kuiper Belt before being knocked inwards. But while comets have been warmed and changed by the Sun, New Horizons offered the first chance to look at these worlds close-up in their natural habitat, and the researchers weren't going to be happy with looking at just Pluto.

It would only take a little nudge to send New Horizons towards another target. But first, the team needed to find one. Fully surveying the New Horizons flight path for KBOs took several years, but in 2014 they found one – Arrokoth (previously nicknamed Ultima Thule).

MASS APPEAL

From what we know of the Kuiper Belt via long-range observations, Arrokoth is much more typical of other KBOs in terms of its size and colour than Pluto. A flyby would give a far more representative look at what a body in the Kuiper Belt looks like.

Despite the difficulties in aiming at a world just 36km long and over 6.6 billion kilometres away, New Horizons successfully sped past on New Year's Day 2019. The data download from Arrokoth will take until 2021, but it's already yielding momentous results. Arrokoth is what's known as a 'contact binary', meaning it's formed from two separate bodies that have stuck together. It is thought that the planets in the Solar System grew from small space rocks that clumped together to ever increasing sizes, so Arrokoth is the perfect place to test theories about how this process worked.

"There are two basic theories of how small bodies formed in the Solar System," says Stern. "One says they formed from the collision of bodies from distant regions of the Solar System. The other theory says they form from objects only made locally around themselves in what's called the 'cloud collapse model'. We can determine that the local cloud collapse model fits with the geology of Arrokoth, deciding a long-standing scientific controversy between the two theories of how the planets form."

There is still much for New Horizons to do beyond simply sending its data, however. There's a chance for another flyby and Stern's team are preparing a hunt for more potential targets. Once again, the search will take several years – until at least 2022 – but this time, the flight team are working against the clock.

"The Kuiper Belt only runs out a finite distance," says Stern. "By 2027 or 2028 we will exit the Kuiper Belt. We must find and intercept an object by that date or we will be past the Kuiper Belt and the possibility of a flyby will end."

If these searches do come up empty, the mission is still far from over. It is the first spacecraft to pass through these outer regions of our Solar System since the Voyager probes. Updated with 30 years' worth of technological advancements, New Horizons can look for things that the Voyagers could not.

"We've already seen evidence of a vast structure of hydrogen gas in the outer Solar System," says Stern. It was predicted decades ago but was never observed until New Horizons. "We also observed pick-up ions. These are atoms from interstellar space that have become part of the heliosphere – the environment of the Solar System. Again, they have been predicted for many years, but Voyager didn't have the right spectral range to discover them."

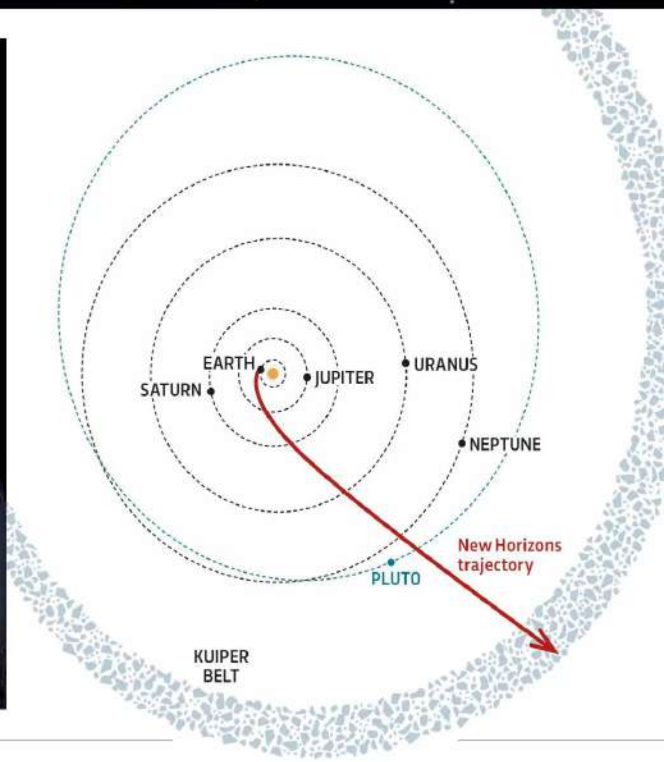
The spacecraft is also carrying the first ever dust detector to travel beyond the orbit of Uranus, allowing the New Horizons team to map the distribution of dust in the Kuiper Belt. The researchers are watching to see if particles smoothly tail off towards the edge of the disc, or if they suddenly drop off.

ABOVE Visualisation of the trans-Neptunian object, contact binary Arrokoth, the most distant object visited by a human spacecraft

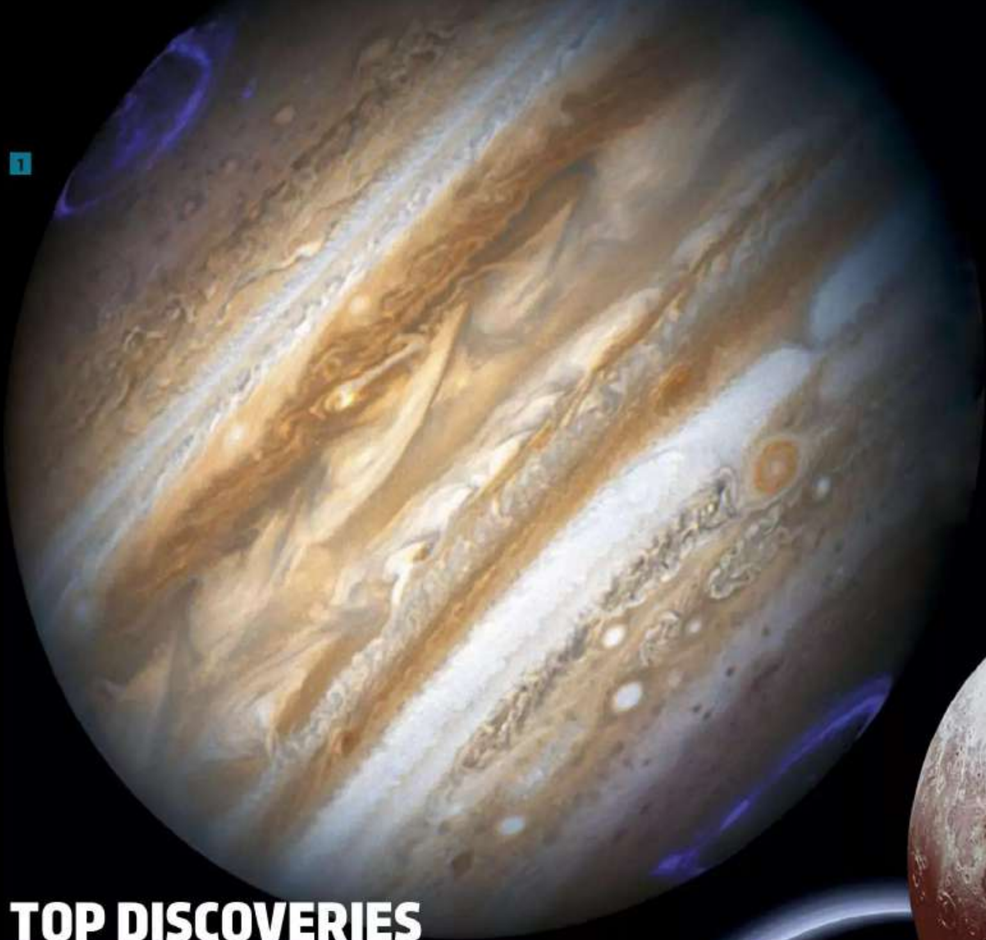
RIGHT Pluto's 'Brilliant Heart' is rich in rich in nitrogen, carbon monoxide and methane ices. The western lobe is captured here by New Horizons

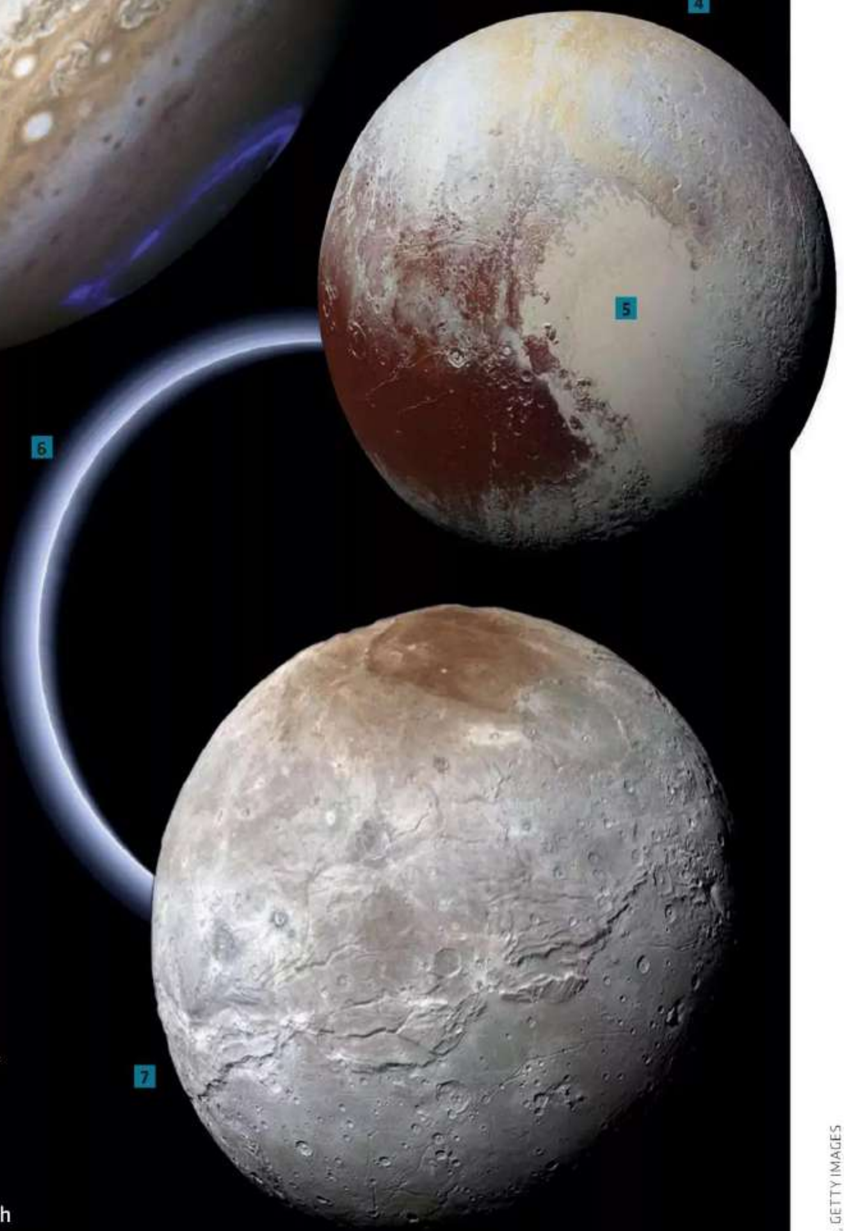
FAR RIGHT Overhead view of the New Horizons trajectory through the Solar System as it entered the Kuiper Belt

GETTY IMAGES, NASA



EARTH
SATURN
JUPITER
URANUS
NEPTUNE
New Horizons trajectory
PLUTO
KUIPER BELT





TOP DISCOVERIES

The New Horizons mission has revolutionised our understanding of the icy bodies in the outer Solar System

1. LIGHTNING ON JUPITER
New Horizons stopped by Jupiter on its way to Pluto, spotting lightning in the clouds over the poles.

2. KUIPER BELT OBJECTS FORM LOCALLY
Studying Arrokoth helped scientists determine the planets formed out of nearby material.

3. WALNUT AND PANCAKE
Arrokoth has a weird shape. One lobe is wide and flat, like a pancake, while the other is rounder.

4. PLUTO IS ACTIVE
Geologists were expecting to find Pluto a geologically dead world, but in reality it's highly active. This activity is filling in Pluto's meteor craters, giving the dwarf planet's surface a youthful smoothness.

5. PLUTO'S HEART
Pluto's heart-shaped nitrogen glacier, Sputnik Planum, is 1,000km wide, making it the largest known glacier in the Solar System.

6. SKIES OF BLUE
Pluto is surrounded by a blue haze, most likely caused by methane in the atmosphere.

7. RED MOON
Pluto's largest moon, Charon, is covered in a red material, formed from gases which escaped Pluto's atmosphere.

8. SPINNING SATELLITES
Pluto's four other moons (Hydra, Nix, Kerberos and Styx) spin faster than any other known satellite in the Solar System.

9. PICKED-UP IONS
New Horizons observed the solar wind slowing down as it mixed with atoms from interstellar space.

NASA X5, GETTY IMAGES

Illustration of a field of debris following the collision between two ice-rich Kuiper Belt objects

There are plenty of scientific communities clamouring to use the spacecraft to observe this seldom visited region. For the time being this research is limited, as Stern wants to preserve the fuel in case another flyby presents itself.

"I often call myself 'fuel hoarder in chief'," says Stern. "There's only so much fuel in the tank. If we discover a flyby but can't reach it because we used part of the fuel for other purposes, that would be scientifically tragic."

If there is no third Kuiper Belt flyby, or there's still fuel left after it, then the spacecraft's cameras could be pointed back at the inner Solar System to give a unique view of the planets, comets and asteroids from the outside. New Horizons is also outside of the dusty environment of the inner Solar System, and so its instruments could be pointed towards the wider Universe to take advantage of the clear view of distant objects across the void of space.

"If we discover a flyby but can't reach it because we used the fuel for other purposes, that would be scientifically tragic"

TIME IS RUNNING OUT

But no one lives forever, and neither does a spacecraft. The nuclear power source on New Horizons is only expected to last another 20 years. Travelling at around 500 million kilometres per year (about the distance from Earth to Jupiter), it should be out at around 100AU by this point, meaning the team will aim to investigate one final region before the spacecraft dies – the outskirts of the heliosphere. New Horizons is unlikely to reach the very edge, as the Voyager probes found it is located around 120AU out, but there is a chance the spacecraft could make it.

"The boundary between the heliosphere and interstellar space breathes in and out because of the Sun's 11-year cycle of activity," says Stern. "We know where New Horizons will be very accurately but we don't know where the boundary is. If it's closer, we'll cross it. If it's further out, we'll run out of power."

What exactly New Horizons will do with the rest of its time is uncertain, but it is clear that with fuel left in the tank and 20 years on the battery, its mission is far from over. **SF**

by **DR ELIZABETH PEARSON** *(@EzzyP)*
Elizabeth is a space journalist and news editor at BBC Sky At Night *magazine.*

INTO THE UNKNOWN

The twin Voyager probes are now exploring interstellar space

by DR ELIZABETH PEARSON

QUICK FACTS

LAUNCH DATES:
Voyager 1: 5 Sept 1977, *Voyager 2*: 20 Aug 1977

DISTANCE TRAVELLED AS OF JANUARY 2020:
V1: 22,246,465,086km, *V2*: 18,483,483,599km

DISTANCE FROM THE SUN AS OF JANUARY 2020:
V1: 22,144,959,920km *V2*: 18,365,602,503km

FINAL MISSION PURPOSE:
The Voyager Interstellar Mission (VIM) aims to extend the NASA exploration of the Solar System to the outer limits of the Sun's sphere of influence, and beyond.

For 40 years, the twin Voyager spacecraft have sailed through our Solar System, pushing humanity's knowledge of the cosmos ever outward. Launched in 1977, the probes took advantage of a rare alignment of the outer planets (Jupiter, Saturn, Uranus and Neptune), flying past Jupiter in 1979, before travelling onto Saturn in the early 1980s. Voyager 1 took a detour for a closer look at the rings, but this swung its orbit northwards out of the plane of the planets. Voyager 2 carried on alone, flying past Uranus in 1986 and Neptune in 1989, marking the end of Voyager's planetary mission.

But it also marked the start of Voyager's next phase, the interstellar mission to investigate the outer regions of the Sun's heliosphere. "The heliosphere is the bubble created by the solar wind," says Ed Stone, Voyager's project scientist since 1972. "The solar wind is travelling from the Sun at supersonic speeds, around 400km/s, and we knew at some point had to run into the interstellar wind."

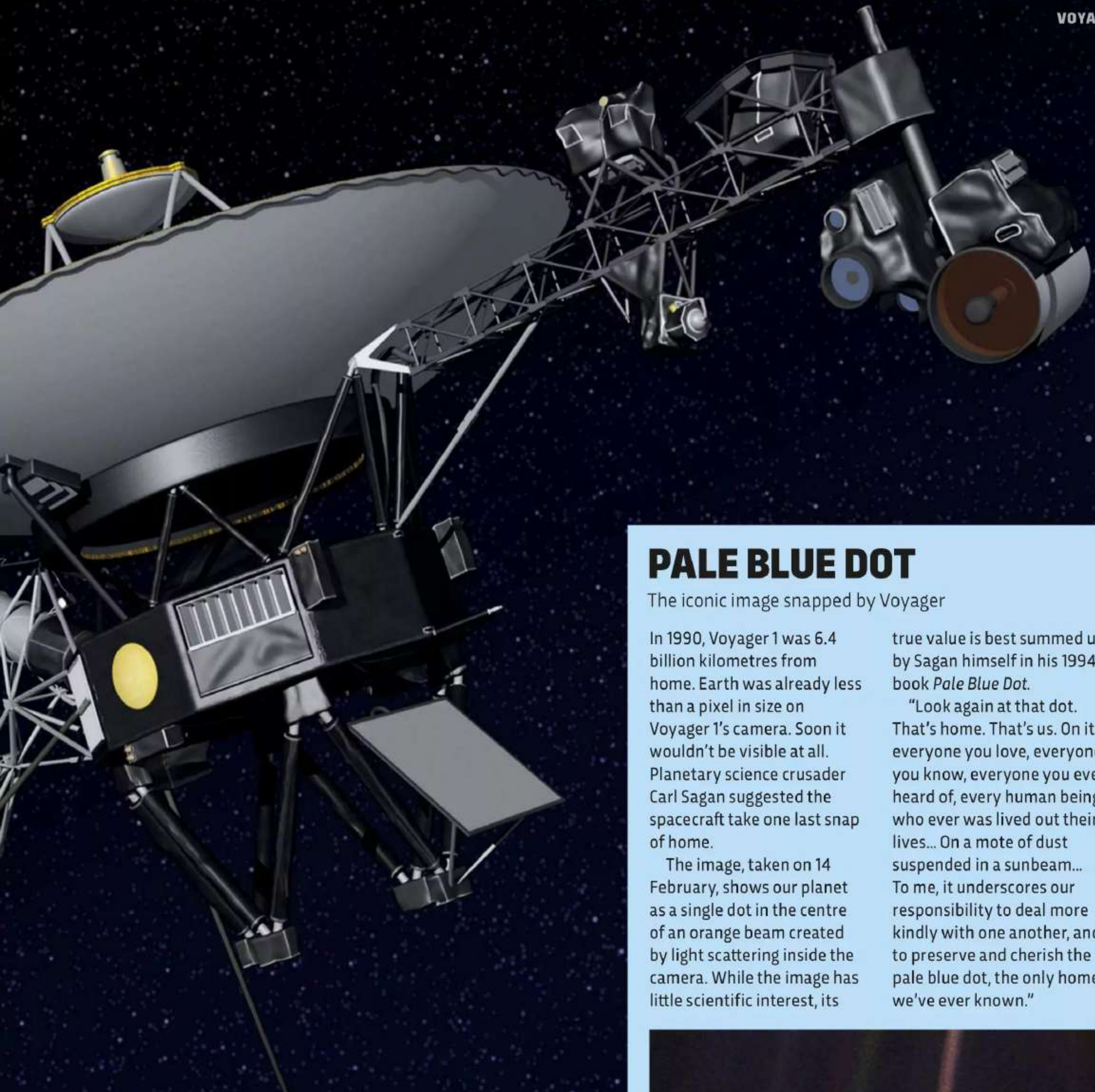
Voyager 1 was the first to reach the edge of the heliosphere, known as the heliopause, in August 2012. When it was 150 million kilometres from the Sun (about 120 times the Earth-Sun distance), the spacecraft detected an uptick in the number of particles originating from other stars. Voyager 2 followed suit in November 2018 when it was roughly the same distance out.

The Voyagers are now taking humanity's first in-situ look at the cosmos beyond our local solar neighbourhood, but at more than 40 years old, the spacecraft are feeling their age. By modern standards, their instruments are simple and only capable of basic measurements of particle energies and magnetic field strength and direction. To make matters worse, the Voyager's nuclear generators are running out of power, forcing the team to shut down instruments to conserve energy. Even so, they only expect the mission to last another five to 10 years.

"From an engineering point of view, it's a new phase of the mission. We have to operate the spacecraft in conditions it was never designed for. We are doing all we can to extend our knowledge as far out into interstellar space as possible but leave it for some future mission to go further," says Stone.

So far, only New Horizons, which flew past Pluto on 14 July 2015, has picked up that baton. It too is heading towards the heliopause, but its own power source might also give out soon. Though there are ideas for an interstellar

After completing their primary mission to explore Jupiter and Saturn, the two Voyager probes are continuing into interstellar space



probe that will venture out 10 times farther than either Voyager, it has yet to be selected for construction and may never come to light.

Rather than lamenting their mission's slow demise, however, the Voyager team chose to celebrate how far they've come.

"I think it's a very exciting thing," says Stone. "These are the first spacecraft to leave their stellar bubble and so now we're learning what we can in the time we have left before they become our silent ambassadors orbiting the Milky Way for billions of years." **SF**

by **DR ELIZABETH PEARSON** *(@EzzyP)*
Elizabeth is a space journalist and news editor at BBC Sky At Night *magazine.*

NASA/JPL

PALE BLUE DOT

The iconic image snapped by Voyager

In 1990, Voyager 1 was 6.4 billion kilometres from home. Earth was already less than a pixel in size on Voyager 1's camera. Soon it wouldn't be visible at all. Planetary science crusader Carl Sagan suggested the spacecraft take one last snap of home.

The image, taken on 14 February, shows our planet as a single dot in the centre of an orange beam created by light scattering inside the camera. While the image has little scientific interest, its true value is best summed up by Sagan himself in his 1994 book *Pale Blue Dot*.

"Look again at that dot. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was lived out their lives... On a mote of dust suspended in a sunbeam... To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known."


N I
PLA

N E T N E

Beyond Neptune, a handful of small worlds are moving in harmony. Astronomers think they might be dancing to the tune of another world lurking in the darkness, one that's four times bigger than Earth and significant enough to be named our Solar System's ninth planet. Now they think they know exactly where to look for it...

by COLIN STUART

ILLUSTRATION: MAGIC TORCH

Look up at the night sky and find the famous three stars of Orion's Belt. Then extend the line between them up and to the right towards the constellation of Taurus, The Bull. Halfway between them sits a small patch of otherwise unremarkable sky that could well be home to one of the most famous finds in astronomical history – a ninth planet orbiting the Sun. It isn't every day a new planet is discovered in the Solar System. In fact, by one measure, it has only happened twice before in all of human history with Uranus (1781) and Neptune (1846). All the other planets have been known since antiquity and were never really 'discovered'. Objects such as Ceres (the largest asteroid) and Pluto were once deemed part of the planet club, but have since had their membership revoked. William Herschel, Urbain Le Verrier, Johann Gottfried Galle and John Couch Adams are the only astronomers to ever find a new planet that is still considered as such.

That elite list may soon be about to grow. CalTech astronomers Mike Brown and Konstantin Batygin are among the frontrunners to join it. Back in 2016 they went public with the radical notion that the roll call of planets orbiting the Sun isn't finished. They had noticed a handful of small worlds beyond Neptune behaving mysteriously, and considered that perhaps a ninth planet could account for their strange motion. "We were confident that another planet could explain the features of the outer Solar System," says Batygin. They've been scouring the sky for this object, but so far it has escaped them. For now, this potential world goes by the moniker of Planet Nine. If and when it is discovered, it will be named after a Roman or Greek deity, just like the other planets.

LONG-DISTANCE RELATIONSHIP

Planet Nine's suggested existence is based on observations over the last decade with telescopes big enough to peer into the murky environs beyond the eight known planets. Studying this under-explored wilderness is a real challenge. We only see thanks to reflected sunlight, and for these trans-Neptunian objects (TNOs) that light has to undergo quite a journey. The odyssey starts at the Sun, then travels out to a distance of more than 4,500,000,000km, before bouncing off an object and making the return trip to the Earth almost all the way back to the start. That light is also fading all the while, making it very faint and requiring a big telescope to collect it. Take the 600-kilometre-wide object known as 2012 VP113. It sits 80 times further from the Sun than the Earth, meaning the light we see reflected from it is around 40 million times dimmer than normal sunlight. Despite travelling at 300,000 kilometres per second, light takes nearly a day to cover the full distance from the Sun to VP113 and back to the Earth.

"WE WERE CONFIDENT THAT ANOTHER PLANET COULD EXPLAIN THE FEATURES OF THE OUTER SOLAR SYSTEM"

ALAMY, SCIENCE PHOTO LIBRARY X2

It was the discovery of VP113 by astronomers Scott Sheppard and Chad Trujillo in 2014 that first flagged up the possibility of an undiscovered planet. They are another team currently hunting down Planet Nine. Closer scrutiny of VP113's path around the Sun showed that it shared orbital characteristics with another TNO called Sedna. The angle at which they approach the Sun is eerily similar. Our best theories of Solar System formation say that for each object this tilt should be random. So the fact that these two objects match arouses suspicion. "They're like the fingerprints and broken glass of a crime scene," says Megan Schwamb from the Gemini Observatory in Hawaii and co-discoverer of several TNOs. "Who did it?". One explanation is to point the finger at a ninth planet, whose gravity is pulling on these objects and organising their orbits. To be doing that it would have to be several times the mass of the Earth. It wouldn't be the first time we've found a new planet this way. After Uranus was discovered, discrepancies in its orbit were put down to the tug of another planet even further out. Sure enough, when astronomers calculated where this planet would be they discovered Neptune. Now teams of astronomers including Brown, Batygin, Sheppard and Trujillo are trying to do the same with Planet Nine.

HIDE AND SEEK

So far the planet remains stubbornly out of view, but the search has cemented the evidence that it is really there. In the process of trawling the outer Solar System, astronomers have uncovered new TNOs. We now know of 14 objects clustered together more than 230 times further from the Sun than the Earth. This includes an object nicknamed The Goblin, discovered by a team of astronomers including Sheppard and announced in October 2018. It's a 300-kilometre-wide TNO on a highly elongated 40,000-year loop around the Sun. The more of these objects that we find sharing similar tilts, the stronger the case for Planet Nine becomes.

But there are alternative explanations. The leading one is that these copycat orbits are nothing more than observational bias. There are thought to be millions of TNOs out there that we haven't found yet, all with

TOP: The five confirmed dwarf planets in our Solar System and their moons. From left to right: Pluto; Eris; Makemake; Ceres; Haumea

MIDDLE: The region of sky between Orion's Belt (yellow circle) and Taurus (white circle) is the search area for Planet Nine

BOTTOM: Artist's impression of Planet Nine

FAMOUS OBJECTS BEYOND NEPTUNE

SEDNA

Discovered by Mike Brown, Chad Trujillo and David Rabinowitz in 2003, Sedna was one of the objects that forced astronomers to re-evaluate Pluto's planethood. It takes 11,400 years to orbit the Sun, crawling along at an average speed of just one kilometre per second. Sedna will make its closest approach to the Sun in 2075–2076, providing a once in an 11,400-year opportunity to get the best view of this world named after the Inuit goddess of the sea.

2012 VP113

This object is often nicknamed 'Biden' after Joe Biden, who was the US vice-president at the time of its discovery at the Cerro Tololo Inter-American Observatory in Chile. At 600 kilometres wide, astronomers believe its pink colouration is due to the way cosmic radiation has shaded its surface, which is made of water and/or methane ice. It doesn't get as close to the Sun as Sedna, nor as far away. Sedna and Biden were the original basis for the Planet Nine idea.

random orbits. It could just be a fluke that we've happened upon the handful that do share similar paths around the Sun. If this were true, Planet Nine would be a figment of our imaginations. But in January 2019 Brown and Batygin published new research attempting to quantify how likely this is based on the latest TNO discoveries. Their answer? Just 0.2 per cent. "That's our most conservative estimate," says Batygin. A ninth planet, they claim, is the only existing explanation for what we see in the outer Solar System.

SCOURING THE SKIES

That doesn't mean finding it is easy. All searches so far have failed to spot the planet. The hunt is not helped by the fact that there are only a handful of telescopes in the world capable of seeing it. Not only do you need a large aperture telescope to collect the faint light, you also need one equipped with a camera with a wide field of view. Brown is using the 8.2-metre Subaru telescope in Hawaii to hunt for it, while Batygin is busy crunching the numbers. "The search area is 800 square degrees of sky," says Brown. That's about the same as 3,200 full Moons. A telescope with a narrow view would just take too long to cover this vast expanse.

It's not a two-dimensional patch of sky either, but three-dimensional. We also don't know Planet Nine's exact distance from the Sun. If it is near it will be brighter and if it's further away it will be dimmer. When it comes to the brighter end, Brown says they've already covered nearly all of the sky where it might be hiding without success. "That's surprising to me," he says. "That would have been the most reasonable guess of what Planet Nine would be like."

The findings are all the more unexpected when Batygin's latest computer modelling is

"A NINTH PLANET, THEY CLAIM, IS THE ONLY EXISTING EXPLANATION FOR WHAT WE SEE IN THE OUTER SOLAR SYSTEM"

GETTY IMAGES

THE GOBLIN

Named because it was discovered close to Halloween, The Goblin was first observed on 13 October 2015 using the Mauna Kea Observatory in Hawaii. It took three years to track it in sufficient detail to pin down its orbit and announce the discovery to the public. The Goblin's highly elongated orbit carries it from roughly twice Pluto's distance from the Sun all the way out to 30 times further than that. It's about as bright as one of Pluto's smaller moons.

FAROUT

Astronomers like to keep things simple where they can, as illustrated by the nickname of this object found on 10 November 2018. A name like FarOut marks that, at the time of its discovery, it was the furthest object ever found in the Solar System. Unfortunately this wasn't kept as its official name, and it became 2018 VG18. Looking back at older photographs actually shows that FarOut had been captured before in 2015 and 2017. Like VP113, it appears to be pinkish in colour.

FARFAROUT

FarOut didn't hold its crown as a record breaker for long. In February 2019 a team led by Scott Sheppard announced the discovery of an object even further out – nicknamed FarFarOut. This time it is 140 times further from the Sun than Earth (or 21 billion kilometres). Both objects have been found so recently that their orbits are still being determined to see if they support the Planet Nine theory.

Mike Brown (left) and Konstantin Batygin (right) are searching the skies for objects beyond Neptune, including Planet Nine

HEAD IN THE CLOUDS: The Subaru Telescope on top of Hawaii's Mauna Kea is being used to search the skies for Planet Nine

taken into account. "We've performed thousands of new computer simulations in the last 18 months," he says, all to understand more about where Planet Nine could be. According to Batygin, the upshot of those calculations is that "Planet Nine is smaller in all parameters by a factor of two compared to our original estimates". Its orbital period is now thought to be 10,000 years rather than 20,000. It is five times the mass of the Earth, not 10. Despite being smaller, its shorter orbit would make it about two and half times brighter than the original 2016 estimates.

"NATURE HAS NO OBLIGATION TO YOU. LOOK AT GRAVITATIONAL WAVES – THEY TOOK 100 YEARS TO FIND"

THE NET IS CLOSING

So how come Brown still hasn't found it, despite trawling the whole area at the brighter end? "We don't know its albedo and that's the key parameter," says Brown. An object's albedo is a measure of how much sunlight its surface reflects back into space. "It could either be a super-cloudy, bright object or a dark ice ball covered in junk with a low albedo." The fact it hasn't been found yet suggests it is the latter. If a dull surface is making it dimmer, finding Planet Nine will take more time. "We've covered about 50 per cent of the sky in that range," he says.

So the net is closing, but it is a laborious process. "The main difficulty is sustaining such an intense search for many years," says Brown. Planet Nine's predicted position out between Orion's Belt and Taurus is both a blessing and curse. Orion is part of the winter sky, which means that astronomers are restricted to searching for it during that season. In the summer it is part of the daytime sky and therefore undetectable. On the plus side, winter nights are longer, but the emphatic downside is that in recent years the winter weather in Hawaii has been horrendous. Batygin recalls one occasion where he was driving up the volcano to the telescope with hailstones the size of golf balls slamming into the car. On another occasion the weather looked clear, but Brown arrived at the telescope to find the door to the telescope was frozen shut. "We've had every sort of obstacle you can imagine," says Brown. Other roadblocks have included volcanic eruptions, earthquakes and sulphur dioxide fumes. "It's frustrating," he says. "[I'd] like to find it and move on to something else." With winter drawing to a close, the season is almost done and the search will soon have to wait until the Earth moves back round to the favourable side of the Sun. Batygin sums it up nicely: "Nature has no obligation to you," he says. "Look at gravitational waves – they took 100 years to find." If the current searches fail, there's hope on the horizon in the form of the Large Synoptic Survey Telescope (LSST). Currently under construction in Chile, its 3.2 billion pixel camera will be capable of photographing an area of sky the size of 49 full Moons at once. It's due to start operation in 2022. Even if it doesn't find Planet Nine right away, it is expected to discover hundreds of new TNOs. If their orbits also share the tell-tale alignment, then that would both strengthen the case for Planet Nine and point astronomers towards where to find it. According to Schwamb, the Planet Nine hypothesis is an answerable question. "It is not going to be a mystery forever," she says.

A deeper puzzle is how Planet Nine got there in the first place. How does a planet five times the mass of the Earth end up marooned up to 20 times further from the Sun than Neptune? The most likely explanation is it formed in the inner Solar System with the other eight planets, before some event threw it out into the depths of space. Even before astronomers found evidence for Planet Nine, computer simulations of the Solar System's formation were hinting at a missing planet. Starting with five giant planets resulted in a Solar System that looks more like ours today than if it started with just four. The only trouble was that there was no other evidence that this extra planet ever existed. Yet if the current frenzy of activity confirms the existence of Planet Nine, it is almost certainly this missing world. Its discovery would mean more than just another planet on the list: it could be the key to understanding why our Solar System looks the way it does today. **SF**

by COLIN STUART
(@skyponderer)
Colin is an astronomy author. Get his weekly space newsletter at ***colinstuart.net/newsletter***

WATCHING THE DETECTORS

WHETHER DEEP UNDERGROUND OR PERCHED ON A VOLCANO, PARTICLE DETECTORS HELP SCIENTISTS TO UNRAVEL THE MYSTERIES OF THE COSMOS

by BRIAN CLEGG

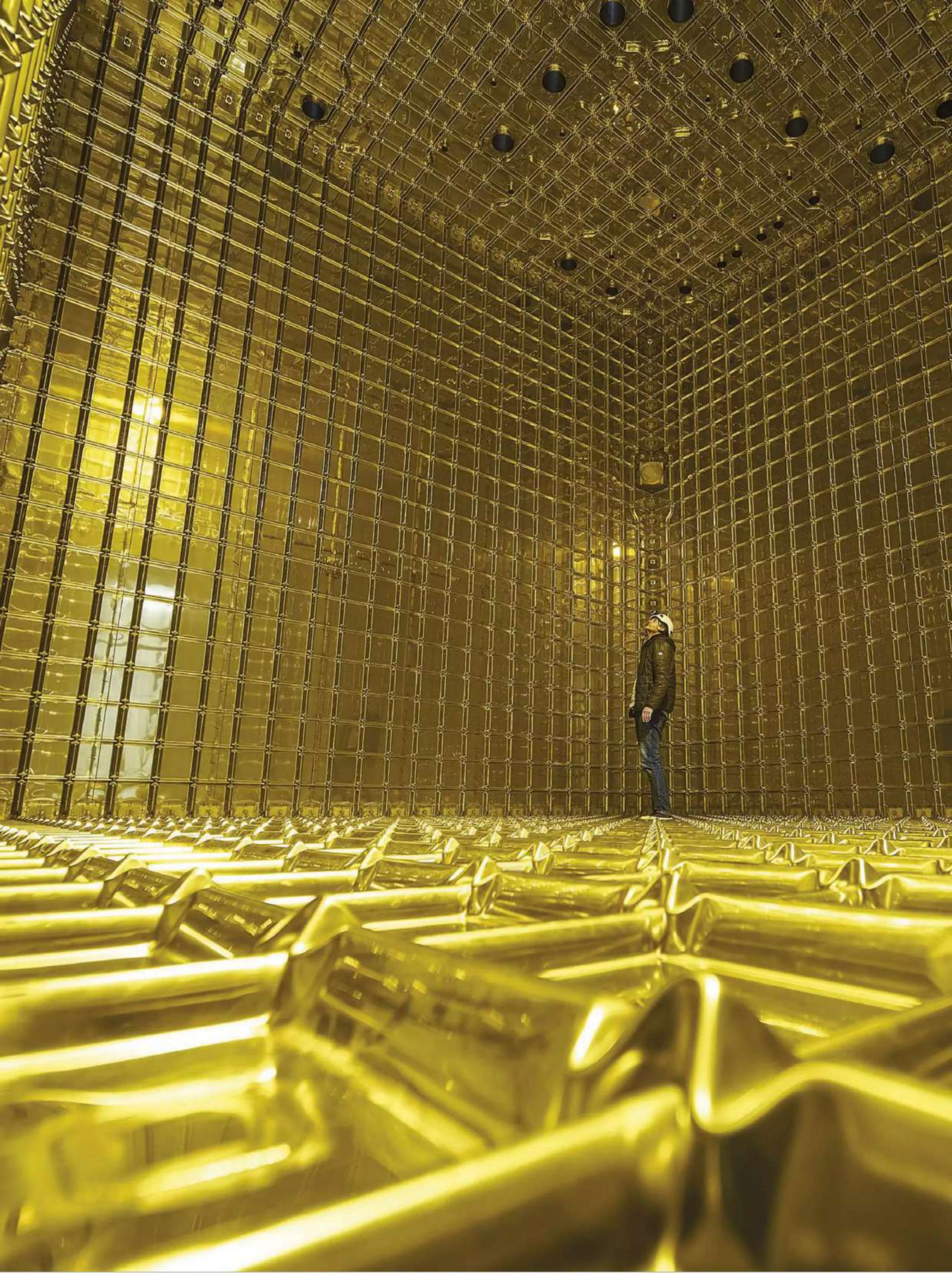
MAXIMILIEN BRICE/CERN

STRIKING GOLD

→ PROTODUNE, FRENCH-SWISS BORDER

DETECTING: **NEUTRINOS**

Bathed in yellow light to avoid overstimulating its sensors, this neutrino detector is the size of a three-storey house. Neutrinos are abundant – trillions pass through you every second – but they hardly interact with matter, making them tough to detect. When in operation, ProtoDUNE is filled with 800 tonnes of liquid argon. Sometimes, a neutrino makes a direct hit on an argon nucleus, producing a trail of charged particles detected by grids of wires around the detector. This prototype is being tested at CERN's headquarters, but DUNE (Deep Underground Neutrino Experiment) will be sited 1.5km underground in the disused Homestake gold mine in Lead, South Dakota. With four detectors, DUNE will pick up neutrinos generated by a particle accelerator 1,300km away at Fermilab, near Chicago. Expected to go live in 2026, DUNE will detect differences in behaviour between neutrinos and their antimatter counterpart, antineutrinos, which could help explain why the Universe has more matter than antimatter.



TANKS A LOT

← HAWC (HIGH-ALTITUDE WATER CHERENKOV OBSERVATORY), MEXICO

DETECTING: **GAMMA RAYS**

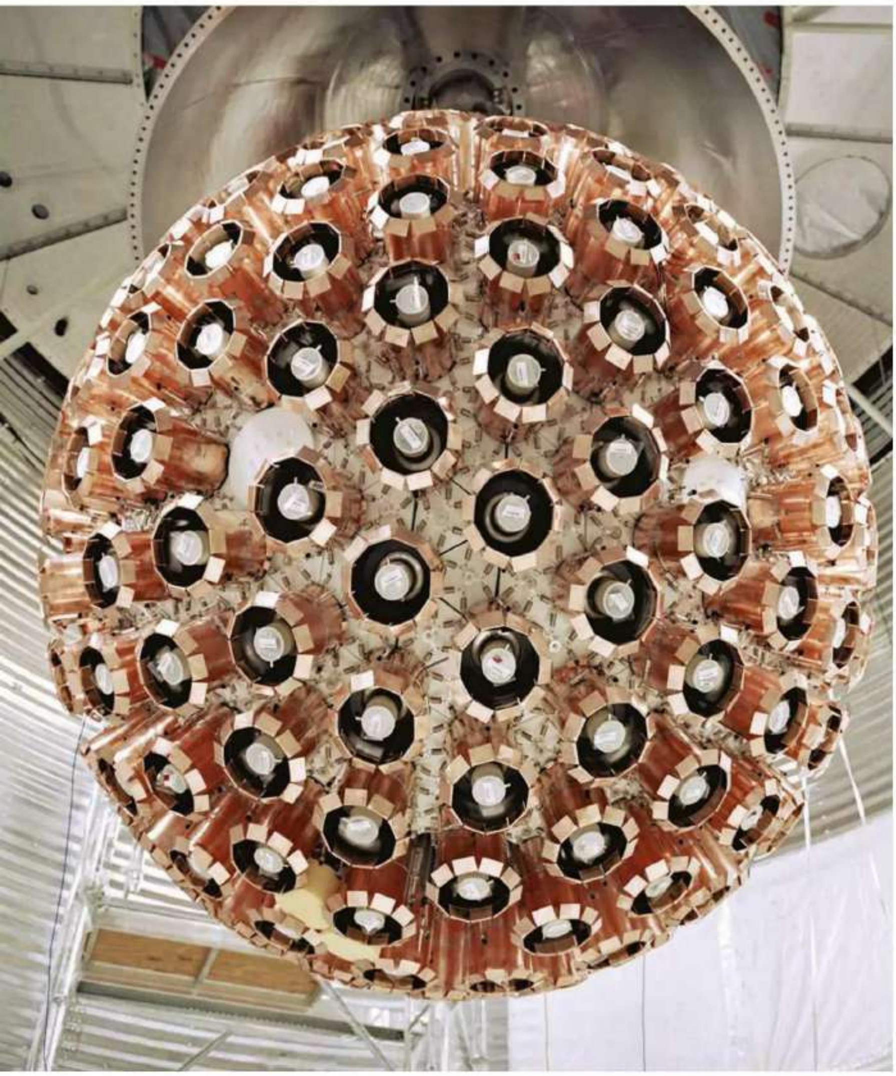
In the shadow of Mexico's Pico de Orizaba volcano, these 300 steel tanks make up the HAWC, which is on the lookout for gamma rays – high-energy radiation created by cataclysmic events in space. When gamma rays hit our atmosphere, they produce a shower of fast-moving particles, which can interact with water molecules to create 'Cherenkov radiation', visible as an eerie glow. Each of the 7m-wide tanks is filled with water, plus detectors for picking up the radiation. HAWC has recently been used to study the SS 433 microquasar, around 15,000 light-years away. SS 433 consists of a black hole consuming a star, pushing out jets of matter that generate gamma rays.

CATCHING WAVES

→ LIGO (LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY), USA

DETECTING: **GRAVITATIONAL WAVES**

This 40kg, red-tinted mirror is suspended by an elaborate system, allowing it to detect movements smaller than an atomic nucleus, indicating the arrival of gravitational waves. Comprising two sites over 3,000km apart, each LIGO site has a pair of 4km-long tubes, through which lasers repeatedly travel, revealing movements in these mirrors. On 14 September 2015, astronomy was changed forever by LIGO's first detection of gravitational waves. Predicted by Einstein in 1916, these vibrations in the fabric of space-time are caused by cosmic collisions like merging black holes. So far, LIGO has detected 11 black hole and neutron star mergers.



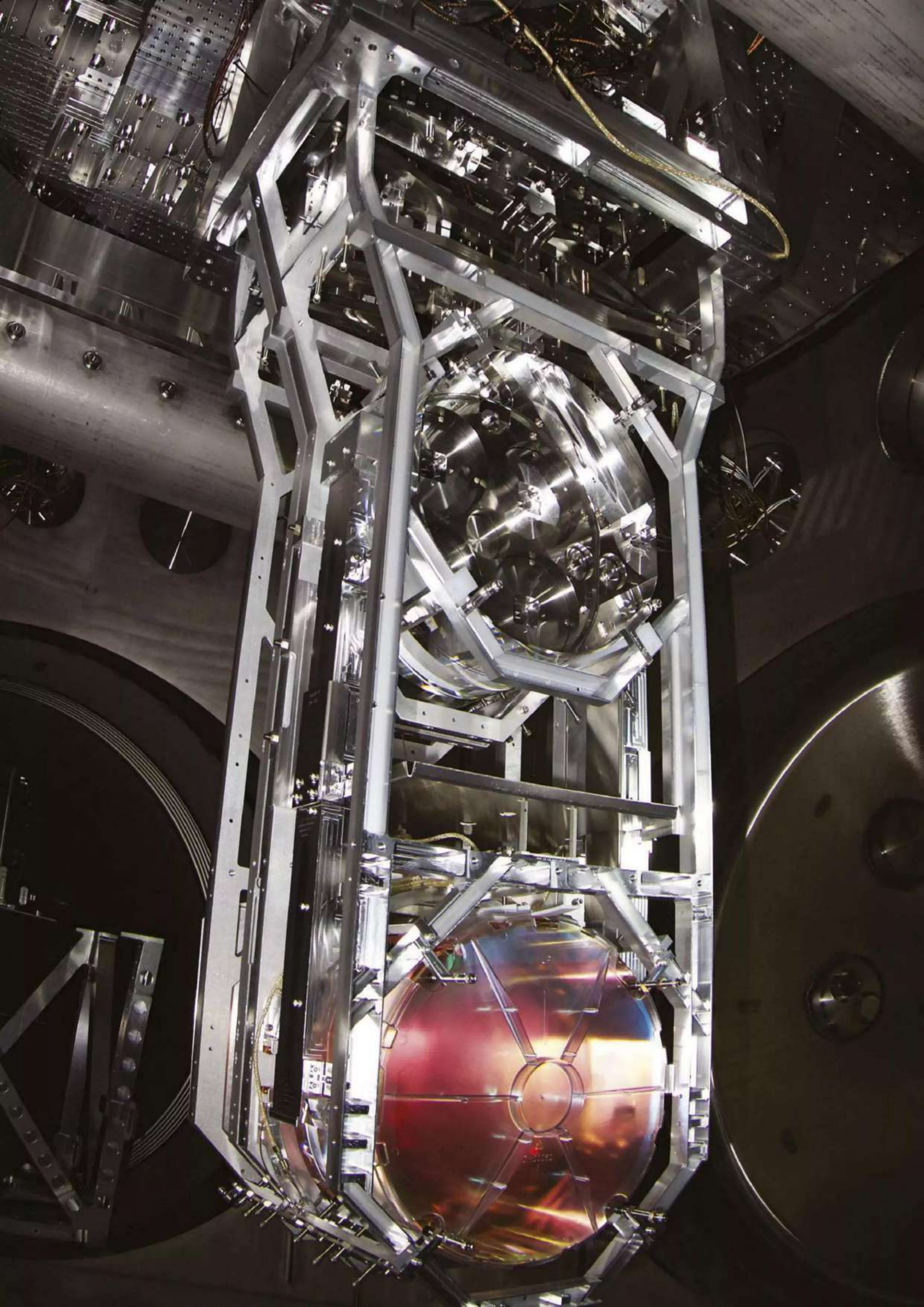
DEEP, DARK SECRET

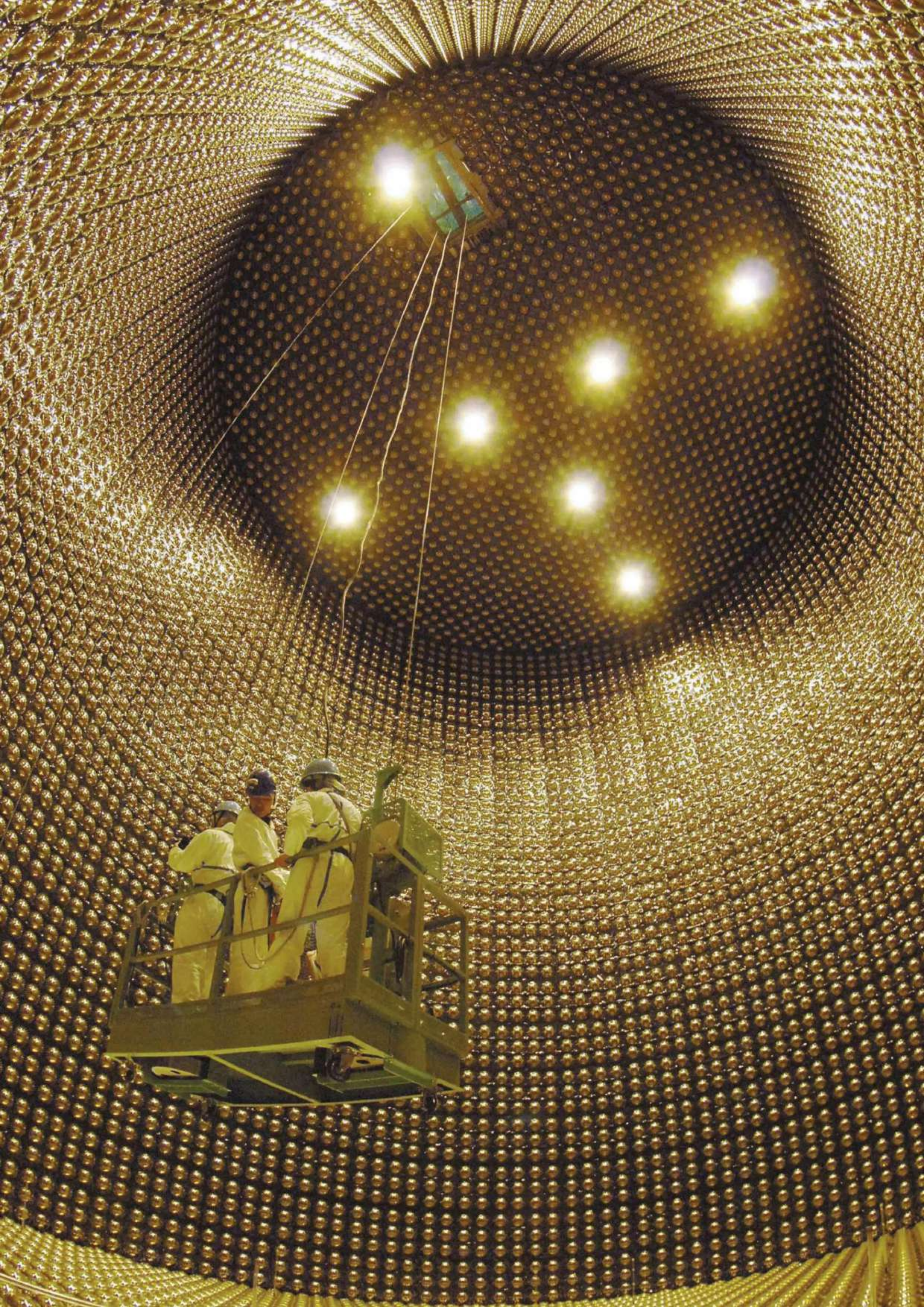
← DEAP-3600 (DARK MATTER EXPERIMENT USING ARGON PULSE-SHAPE), CANADA

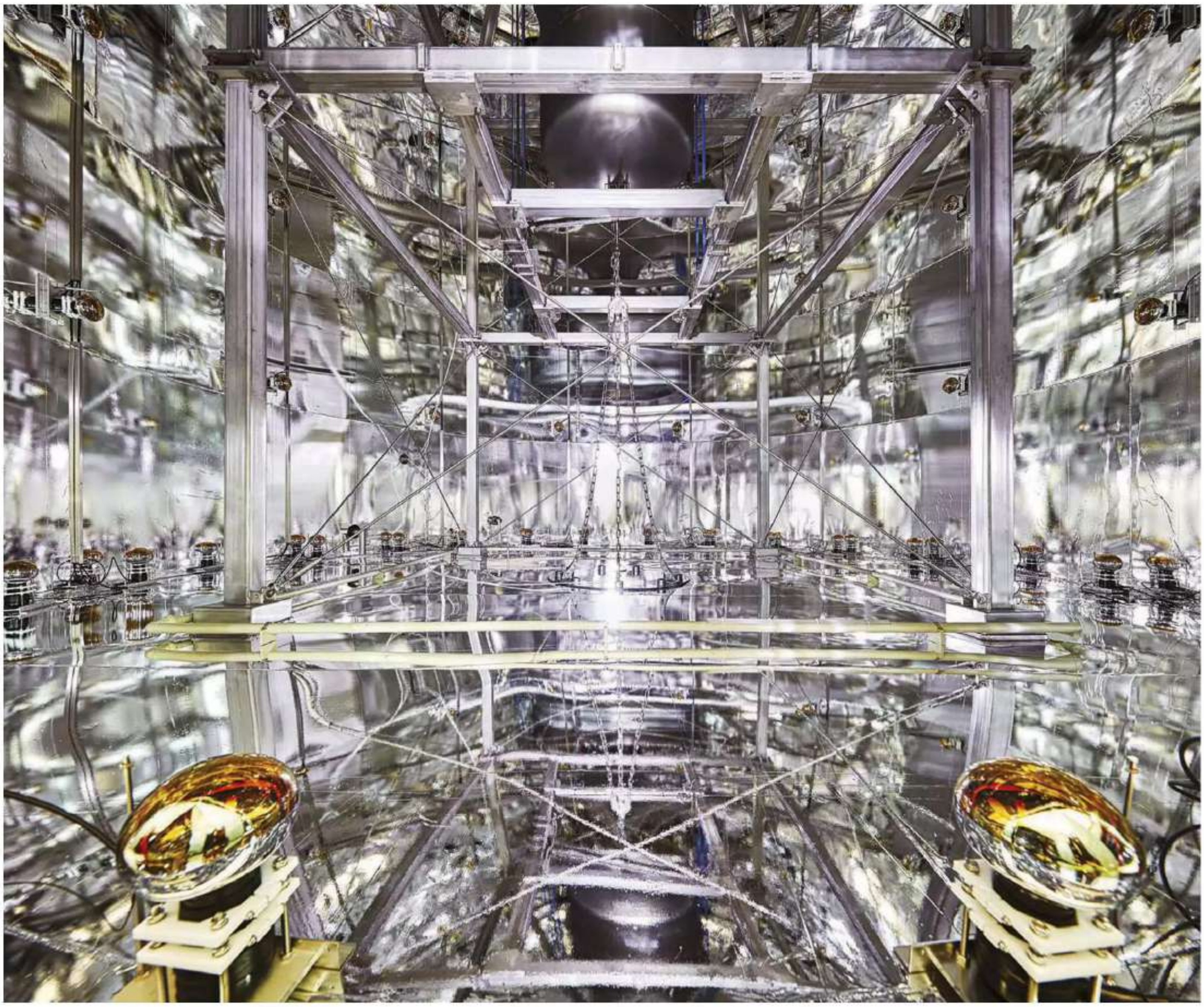
DETECTING: **DARK MATTER**

This flower-like array of photomultiplier tubes in the DEAP-3600 detector surrounds a chamber of liquid argon. The tubes are pointed inwards, looking for tiny flashes of light as incoming dark matter particles interact with the argon nuclei. Dark matter – predicted by measurements that galaxies seem to contain far more matter than is observed – should outnumber ordinary matter particles five to one. One theory is that dark matter is made of WIMPs ('weakly interacting massive particles'), which is what DEAP-3600 is looking for. To reduce interference, the detector is located 2km underground in an old nickel mine at Sudbury, Ontario. DEAP-3600 began operations in 2016, and the first data is just starting to be analysed. So far, nothing has been found.

HAWC OBSERVATORY, NSF/MIT/CALTECH, SNOLAB







LIGHT SHOW

← SUPER-KAMIOKANDE, JAPAN
DETECTING: **NEUTRINOS**

Over 13,000 light-detecting tubes line the Super-Kamiokande neutrino detector, 1km beneath Mount Ikeno in Japan. The 40m-wide tank holds 50,000 tonnes of pure water. When neutrinos collide with the water molecules, they produce fast-moving electrons, generating Cherenkov radiation, detected by the tubes in this photo. Super-Kamiokande has been central to our understanding of neutrinos' weird behaviour. We know that the Sun produces vast quantities of neutrinos, but only about a third of them were being detected. Super-Kamiokande, along with Canada's Sudbury Neutrino Observatory, was used to show that neutrinos go through a process called oscillation, shifting between three different types in flight – which explained why so many were going undetected. This showed that – contrary to expectations at the time – neutrinos have mass, flagging up a gap in our understanding of how the Universe works.

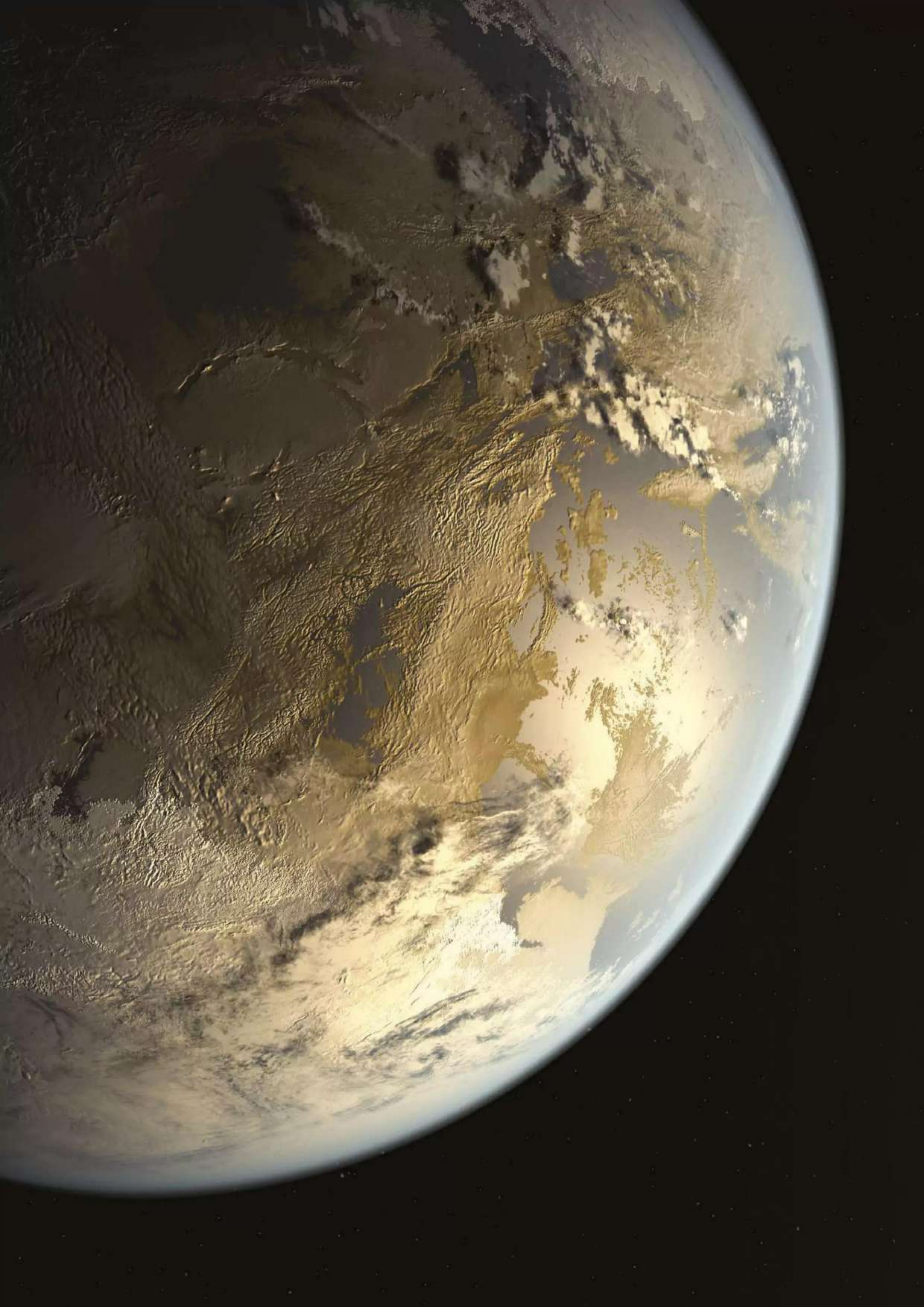
GETTY IMAGES, ENRICO SACCHETTI

WIMP-WATCHING

↑ XENON1T, ITALY
DETECTING: **DARK MATTER**

In operation, the 10m-high outer chamber of XENON1T is filled with water, which shields the central part of the experiment from contaminating particles and radiation. Inside this water chamber sits a super-low temperature fridge, known as a cryostat, which houses 3.5 tonnes of liquid xenon. Situated at the underground Gran Sasso lab in Italy, the aim of this experiment is to spot collisions between xenon atoms and hypothetical dark matter particles known as WIMPs. When xenon atoms and WIMPs collide, they should produce faint flashes of light. The first results from XENON1T were released in 2017, and as yet no WIMPs have been detected. The researchers are building the next phase of the experiment – XENONnT – which will contain eight tonnes of xenon (giving a greater chance of a collision being observed), and is designed to be more sensitive, thanks to lower background radiation. **SF**

by BRIAN CLEGG
(@brianclegg)
Brian is a science writer who has authored more than 30 books. His latest is Scientifica Historica *(£25, Ivy Press), is out now.*



THE HUNT FOR EXOPLANETS

Over the coming years, a new generation of space telescopes will seek out distant planets in the hope of unlocking the secrets of the Universe

by IAIN TODD

In January 1992, two radio astronomers announced a discovery that would change our view of the Universe forever. Aleksander Wolszczan had been scanning the skies to study a type of spinning star known as a pulsar, but something was blocking his view. Curiosity piqued, Wolszczan eventually discovered the root of the interference: two planets in orbit around the star. Fellow radio astronomer Dale Frail verified the data, and the pair made their incredible announcement to the world: they had discovered the first ever known extra solar planets – or 'exoplanets'.

The existence of exoplanets – planets orbiting stars other than our Sun – had long been theorised, but now there was definitive proof. For the first time, humanity could be sure that the Solar System in which it lived was not alone: there were planetary systems out there in the cosmos.

Since this discovery, there has been a concerted effort by astronomers to find even more of these exoplanets. NASA's Kepler Space Telescope, launched in 2009, has confirmed more than 2,300 exoplanets, and revealed that, on average, there is one planet orbiting every star. The next time you look up at the night sky, think about this: for every star you can see, there is probably another world in orbit around it.

Now, a new generation of exoplanet-hunting missions is primed for follow-up investigations to build on Kepler's progress and make discoveries that could change what we know about how planets form, and how life might arise elsewhere in the Universe.

BBC RADIO 4

Listen to an episode of *In Our Time* on exoplanets bit.ly/distantplanets

NASA AMES

Perhaps most exciting is the James Webb Space Telescope (JWST). This orbiting observatory, due to launch in 2021, is expected to make many new discoveries, including the search for exoplanets. JWST is seen by many as the successor to the Hubble Space Telescope, albeit 100 times as powerful and, rather than orbiting Earth, will instead orbit the Sun at a distance of 1.5 million kilometres from our planet. This will help it avoid heat from the Sun, Earth and the Moon and remain cool – around -225°C. Why? Because warm objects emit infrared light, and infrared will be JWST's primary method of observing the Universe.

One of its goals will be to observe young planets forming around young stars. Stellar formation begins when clouds of gas and dust in space begin to clump mass together, growing so big that they eventually collapse under their own gravity. What remains is a young proto-star surrounded by a spinning disc of dust. Out of this dust may form a system of planets orbiting the central star, just like our own Solar System. In optical light these still-forming planets are obscured by the dust, but infrared can peer through it to get an unprecedented look at planetary formation in action.

"We build space telescopes because they can take sharper pictures, due to the fact that Earth's atmosphere is not in the way distorting what we're trying to see," says Dr Jane Rigby, one of the mission's project scientists. "If we want to study most colours of infrared light, then we need to go into space because that light

Engineers work on the mirror of the James Webb Space Telescope (JWST)

cannot shine through our atmosphere."

What's really exciting is JWST's ability to split starlight, a technique known as 'spectroscopy'. By splitting the starlight that has passed through the atmosphere of an exoplanet, scientists can analyse the chemical signatures hidden within and learn much about the properties of that exoplanet – whether it has a lot of water vapour in it, for example, or other chemicals that might reveal something about the processes occurring on its surface.

"For gas giants like Jupiter and Saturn around other stars, we can look at bands of methane to see whether the atmosphere has clouds or whether it is clear," says Rigby. "This is our first chance to understand in detail the atmospheres of exoplanets, and there's a lot of interest in studying rocky planets like our own."

If we are to understand how our Sun, the Earth and the other planets formed, we need to look for examples of planetary formation in action. Until relatively recently, we only had one frame of reference: our own Solar System. Now, we have a wide variety of different stars and orbiting exoplanets to choose from.

"The results of Kepler revealed that there are so many surprises," says Dr Kate Isaak, project scientist of the European Space Agency's CHEOPS (CHaracterising ExOPlanet Satellite) mission, launched in December 2019. "In our Solar System we have smaller, rocky planets closer in, and large planets like Jupiter are further out. But other systems reveal hot Jupiters – huge gas giants that have orbits shorter than a few days around their host star. The geometry of the planet systems we are finding is very different from our own, and this is very exciting."

"By splitting starlight that has passed through an exoplanet's atmosphere, we can learn about its properties"

SEARCHING FOR 'SUPER EARTHS'

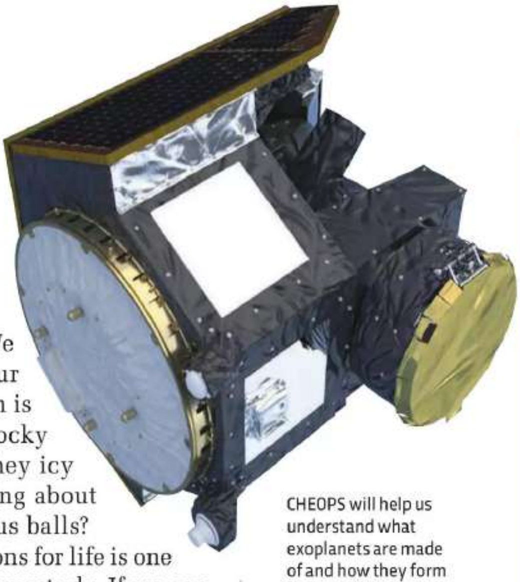
The key aim of CHEOPS is to carry out follow-up observations of bright stars already known to host exoplanets, especially those referred to as 'super Earths' and 'super Neptunes' – exoplanets more massive than their namesakes, yet smaller than gas giants like Jupiter and Saturn.

CHEOPS will measure the regular dip in the brightness of a star as an exoplanet passes in front – known as a 'transit' – enabling scientists to decipher that planet's size, among other properties. Ground-based telescopes will then measure the exoplanet's mass by observing how its gravitational pull causes the host star to 'wobble', which, combined with CHEOPS's transit data will enable astronomers to calculate the planet's 'bulk density'.

"Once we get the bulk density we can then start to work out the structure and composition

FAR OUT, MAN?

Exoplanet-hunting has revealed an abundance of oddities that could have come straight out of a science fiction novel



CHEOPS will help us understand what exoplanets are made of and how they form

of the planets," says Isaak. "We don't have super Earths in our Solar System, so the question is "what are they?" Are they rocky planets like Earth, or are they icy like Neptune? Are we talking about water worlds or small gaseous balls?

Understanding the conditions for life is one of the key aims of exoplanetary study. If we can get a picture of the variety of planets out there in the Universe, we can discover how common rocky planets like Earth are, whether these distant worlds have atmospheres, and whether they orbit in the 'habitable zone', in other words close enough to their star that liquid water can pool on their surface – a key condition for the survival of life as we know it.

JWST and CHEOPS will provide unprecedented studies of exoplanets, but they have to know where to look. This is where NASA's Transiting Exoplanet Survey Satellite (TESS) comes in. TESS was launched in April 2018 and has already begun its mission to monitor over 200,000 stars. It is expected to find over 1,500 potential exoplanet candidates, about 500 of which may be Earth-sized and super Earths.

ARE WE ALONE?

Since our planet is the only cosmic body we know of that harbours life, it makes sense to seek out other rocky, Earth-like worlds in the hope of discovering whether life exists elsewhere in the Universe. One space probe that will be doing just that is PLATO, an ESA mission due to launch in 2026 that will look for small, rocky and icy bodies in the habitable zone around Sun-like stars. This, it is hoped, will enable astronomers to decipher just how common Earth-like planets are, and where to point future missions.

LIFE FINDS A WAY

The extreme conditions on many exoplanets may make them appear uninhabitable, but hardy organisms – known as extremophiles – have shown that life can survive in even the most hostile places.

Cyanidium caldarium is a type of algae known to thrive in hot, acidic conditions. This suggests that life might be able to survive on a planet like Venus, known for its scorching, acidic atmosphere. Meanwhile, *Chroococcidiopsis* is a bacterium found in hot, arid and super salty conditions. Crucially, it can survive radiation, meaning life could potentially survive on planets unshielded from the radiation of their host stars. Microbes have even been found beneath glaciers in Antarctica – cut off from light and oxygen. Could similar organisms be trapped beneath the polar ice caps of Mars?

Perhaps most famous of all extremophiles is the tardigrade. These microscopic creatures have tolerated the extreme radiation and vacuum of space under controlled experiments by ESA. They can survive in temperatures from -272 °C to 150°C, and can live without water for years. What's more, if conditions become too extreme even for them, tardigrades can suspend all but their own vital functions and continue surviving in a form of suspended animation.

Extremophiles show just how robust life can be, and hint at the fact that they may be found even in the most unforgiving corners of the cosmos.

"When I was a kid, we only knew about nine planets, all of them in our own Solar System," says Rigby. "We've since dropped one (Pluto), but learned about a thousand more, and one of the largest surprises is how different many of those systems are. The big question is: how did we get here? How did Earth form? How did the Sun form? How did the conditions for life, with lots of iron and nitrogen – not to mention water – on a rocky world, come to be?"

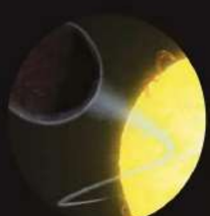
As Wolzsczan and Frail's discovery shows, you never know when the next breakthrough will be made, and curiosity is our best tool for seeking out these astronomical epiphanies. **SF**

by **IAIN TODD**
Iain is staff writer at BBC Sky At Night *magazine.*

55 CANCRI E
Orbits its star 25 times closer than Mercury orbits our Sun, creating a blistering world that reaches temperatures as high as 2,400°C.

KEPLER-16B
This is a planet with two suns, just like Luke Skywalker's planetary abode Tatooine in *Star Wars*.

KELT-9B
This gas giant is about twice the size of Jupiter with a dayside temperature over 4,300°C – hotter than many stars.



WASP-12B'S
This planet's scorching heat allows it to reflect almost no light, making it appear pitch black.

OGLE-2005-BLG-390LB
This rocky planet, about five times the mass of Earth, is likely covered with frozen oceans as its surface temperatures are around -220°C.

GLIESE 436B
This planet is over 300°C. Its gravity compresses the 'burning ice', allowing it to remain solid despite the extreme heat.

DAVID HIGGINGBOTHAM/NASA, ESA X3, ESO, NASA/JPL-CALTECH, NASA/ESA/STSCL/G BACON

ILLUSTRATION: ANDY POTTS

NEW SECRETS OF THE SUPERMASSIVE BLACK HOLE

IN APRIL 2019, SCIENTISTS UNVEILED A PHOTOGRAPH OF A COSMIC PHENOMENON THAT DEFIES THE LAWS OF PHYSICS, MAKING HEADLINES WORLDWIDE. SO HOW DID THEY DO IT, AND WHAT DOES THIS LANDMARK ACHIEVEMENT ACTUALLY TEACH US?

by MARCUS CHOWN

Wednesday 10 April 2019 was an epoch-making moment in the history of science. At six simultaneous press conferences worldwide, an international team of astronomers unveiled the first ever image of a black hole. "It was one of the most exciting days of my life," says Feryal Özel of the University of Arizona in Tucson, who heads the modelling team. "For me, it's the culmination of nearly two decades of work."

In fact, the team observed two black holes: Sagittarius A*, a supermassive black hole in our own Milky Way weighing 4.3 million times the mass of the Sun, and a cousin in the galaxy M87, which is about 1,000 times bigger. The first image revealed is of the supermassive black hole at the heart of M87. Sagittarius A*, because it's smaller, was circled by matter many times while being observed, yielding a blurrier picture.

The image of the black hole in M87, since named Powehi, shows detail smaller than the extent of its event horizon, the point of no return for in-falling light and matter. It is only possible to see such exquisite detail because the intense gravity of each black hole acts like a lens, which makes the image appear five times larger than its horizon.

The horizon in M87 shows up as a dark shadow backlit by intense radio waves, emitted by matter heated to incandescence as it swirls down through an accretion disk (gas and dust that is orbiting the object) onto the black hole. The halo around it is brighter on one side than on the other. "This is because the accretion disk is spinning, causing the light from the part coming towards us to be boosted relative to that from the part that's receding," says Özel.

The remarkable M87 image was obtained by the Event Horizon Telescope (EHT), an array of radio dishes scattered around the globe which have been harnessed together to simulate a giant telescope the size of the Earth. Having an Earth-sized telescope is the key to imaging a target as tiny as a black hole, because the resolution of such a telescope – the fineness of the detail it can discern – depends on the maximum separation of its component parts.

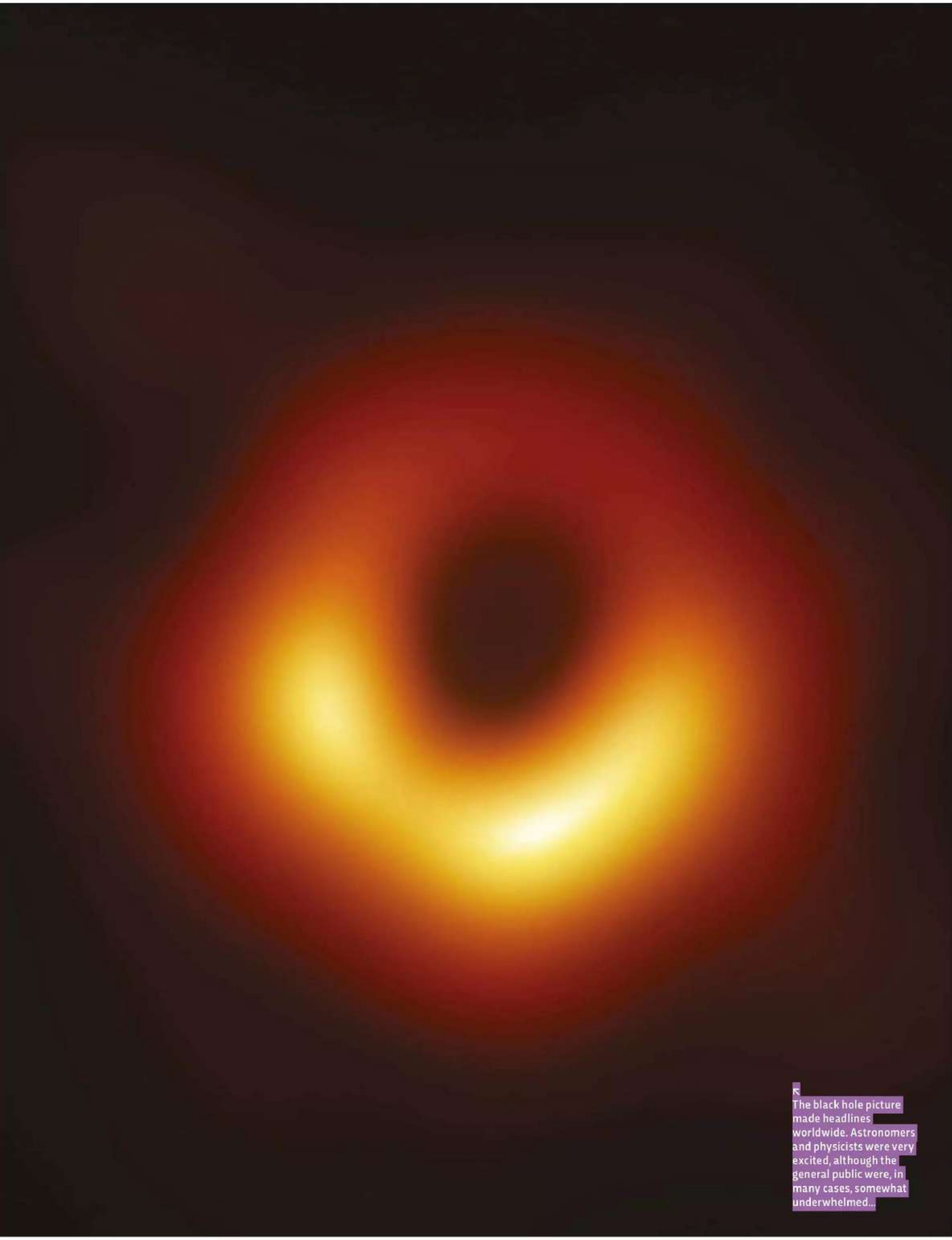
STELLAR OR SUPERMASSIVE?

A black hole forms when matter is compressed into a volume so small that its gravity becomes too intense for anything, even light, to escape. This makes a stellar-mass black hole anywhere in our Galaxy too small for us to see with any Earthbound telescope. But nature has seen fit to create a second population of black holes. These are 'supermassive' ones with masses of up to 50 billion times the mass of the Sun, one of which lurks in the heart of almost every galaxy. However, on account of being very far away, these behemoths are as difficult to image as stellar-mass black holes in our own neighbourhood. Except in two cases: Sagittarius A*, which is just 27,000 light-years away, and its more massive seven-billion-solar-mass cousin in M87, at a distance of 56 million light years. "This is why they were chosen as targets for the EHT," says Özel.

There is also the matter of where to look in the light spectrum. High-energy electrons spiralling in the intense magnetic fields extending from a black hole's accretion disk generate radio waves, which have the advantage that they can easily penetrate the dust shrouding the centres of galaxies and so reach the Earth. Özel is an ➲

"THE EVENT HORIZON TELESCOPE (EHT) IS AN ARRAY OF RADIO DISHES HARNESSED TOGETHER TO SIMULATE A GIANT TELESCOPE THE SIZE OF THE EARTH"

ESO/EHT COLLABORATION



↖ The black hole picture made headlines worldwide. Astronomers and physicists were very excited, although the general public were, in many cases, somewhat underwhelmed...

HOW DO BLACK HOLES FORM?

We're still unsure how the supermassive black holes that lurk in the centre of galaxies, such as Powehi in M87, took seed. Some theories attribute their origin to some of the earliest stars formed in our Universe, while others posit their formation by 'dark matter halos'.

We do, however, have a reasonable understanding of how stellar black holes form...

DYING STAR

Once stars run out of fuel, they die in one of two ways. Smaller, Sun-like stars splutter out of existence and form red giants and white dwarfs, while stars 10 or more times larger go supernova before becoming a black hole.

SUPERNOVA

With the fuel spent, the outward pressure of the nuclear reaction can no longer resist the star's own gravity. The remaining material collapses in on itself and implodes in a supernova, spitting material into space.

COLLAPSE

After this violent explosion, gravity pulls the remaining material together. These gravitational forces crush what's left into a singularity: a single point of almost zero volume but infinite mass, and hence infinite density.

BLACK HOLE

All that mass squeezed into an infinitely small point means that the singularity's gravity becomes so strong that nothing, not even light, can escape its pull, giving rise to what we know as a black hole.

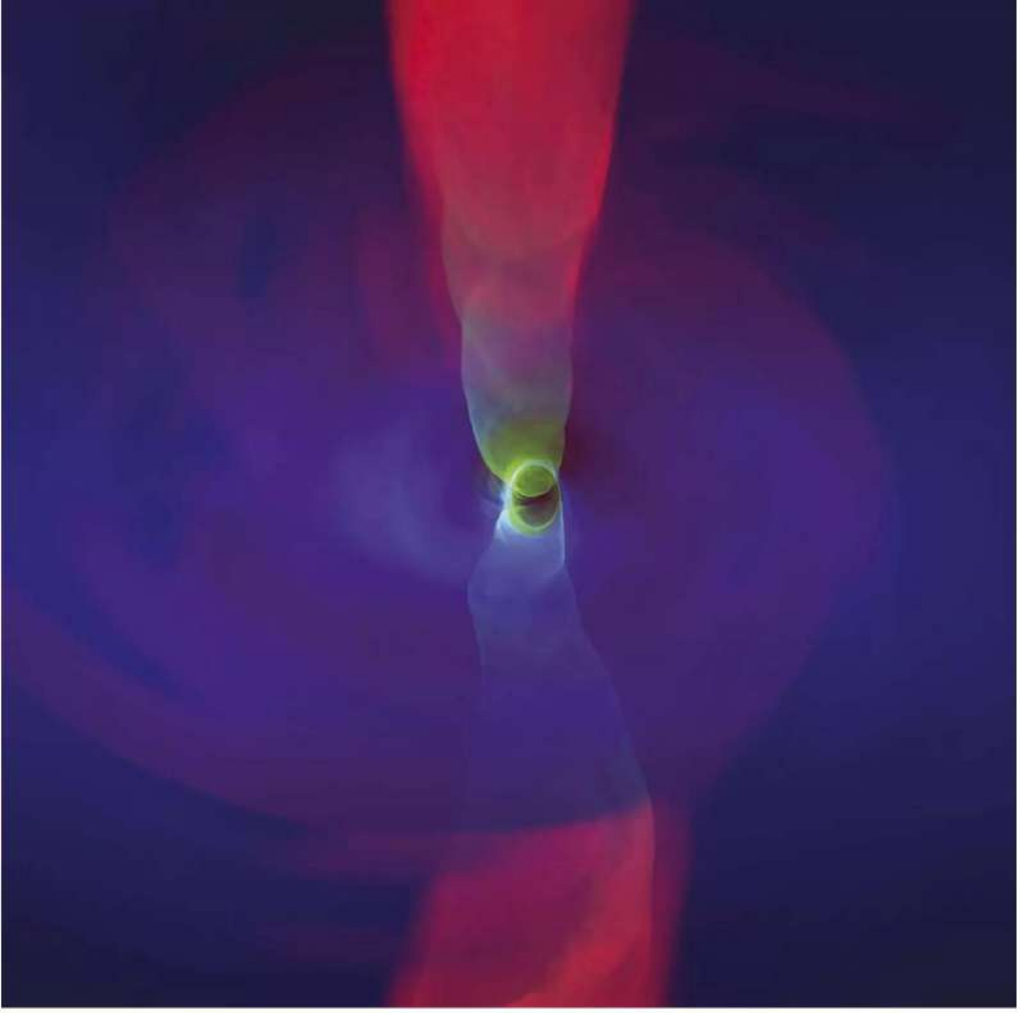
expert in simulating what the turbulent environment of a black hole surrounded by a super-heated accretion disk should look like at different wavelengths. "It turns out that the optimum wavelength is 1.3mm," says Özel. "Not only is it possible to see through the accretion disk to the hole, but our Galaxy and the Earth's atmosphere are transparent to radio waves at this wavelength." Despite this wavelength being used, though, water vapour in the atmosphere can still absorb some of the precious radio waves. For this reason, the EHT's astronomers chose a time of the year to make the observations that maximised the dryness at all telescopes, which are located in places as far-flung as Chile, Hawaii and Greenland. "The optimum time is from the end of March till the end of April," says Özel.

BELOW Kitt Peak National Observatory is the latest telescope to be added to the network of 10 that together constitute the Event Horizon Telescope

In April 2017, the EHT observed with telescopes at eight sites; in 2018, a dish in Greenland was added, upping the total to nine. Now, with the addition of a radio dish at Kitt Peak National Observatory in Arizona, there are 10, but it's the observations made in 2017 that have yielded the images of Sagittarius A* and M87.

In each observing run, data from each site is recorded on hard drives. Ordinary drives malfunctioned in the low pressure at the high-altitude telescope sites, and had to be replaced by special ones developed for the space programme. In 2017, a total of 960 drives, each with a capacity of six or seven terabytes – capable of storing 1-2 billion photos – recorded a whopping five petabytes of data. The disks, which together weighed more than half a tonne, were flown to Massachusetts and Bonn in Germany, where the signals from each site were combined on purpose-built supercomputers known as 'correlators'.

The individual dishes of the EHT can be considered as tiny elements of a filled-in dish the size of the Earth. But whereas the radio waves impinging on each element of a filled-in dish



ABOVE
Until now, computer generated images like this offered the best picture we had of what black holes look like

are reflected to a focus where they are naturally combined, this does not happen for the 'elements' of the EHT. The process must be mimicked by playing back the signals on a computer and exactly reproducing the time delays there would naturally have been between them at the focal point.

Getting the signals perfectly synchronised is only possible because at each dish they are recorded alongside clock signals from a super-stable atomic clock. But combining the signals is still hugely time-consuming, because you need to compensate for delays caused by things such as different atmospheric conditions. This is why it took so long to analyse the data.

Even this tremendous feat of computing is still only half the job, though. Once that's been done, it's still necessary to determine what distribution of matter actually caused the pattern of radio waves observed. "Understanding what's going on requires figuring out what's happening over a huge range of scales," says Özel.

PREDICTIONS PROVED ACCURATE

What's remarkable is that physicists like Özel were so successful, and that the image of the black hole in M87 was so close to what they expected to see. But, although this was cause for celebration among physicists, it left many laypeople underwhelmed, thinking that they had seen it all before. "We are victims of our own success!" admits Özel. "Artist's impressions and movie simulations of black holes, based on physicists' predictions, have turned out to be correct. But those holes were pretend ones. The difference now is that we are seeing the real thing."

Özel says she's "ecstatic" at being part of the team that obtained the first image of a black hole, but that it's also a huge relief. "Our predictions could have been completely off," she says. "Thankfully, we got the physics right!"

Among other things, the image of the nucleus of M87 has yielded the mass of its black hole. The diameter of a hole's event horizon goes up by 6km for each solar mass. Consequently, by measuring the width of the hole in the image and knowing the distance to M87, it has been possible to determine that it weighs in at 6.5 billion times the mass of the Sun. "This chimes perfectly with the mass deduced from how fast the hole's gravity is whirling round nearby stars," says Özel. "That puts it in the top 10 per cent of black holes by mass."

Perhaps the most remarkable thing about the image, however, is the sharp 'photon ring' that marks the inner edge of the doughnut of light around the hole. This is the point at which light plunges across the event horizon, never to be seen in our Universe again. EHT team member Heino Falcke of Radboud University in Nijmegen, the Netherlands, puts it in perspective: "We have seen the gates of Hell at the end of space and time."

"The hole is a part of our Universe permanently screened from view," explains Özel. "A place where our current physics cannot reach."

Our best current description of black holes is Einstein's theory of gravity.

"WE HAVE SEEN THE GATES OF HELL AT THE END OF SPACE AND TIME"

LEFT For Feryal Özel, the image unveiled by NASA on 10 April 2019 was the culmination of 20 years of work

"STEPHEN HAWKING SUGGESTED THAT GENERAL RELATIVITY MAY BREAK DOWN AT THE HORIZON OF A BLACK HOLE"

However, the General Theory of Relativity is likely to be an approximation of a deeper theory, since it breaks down at the centre of a black hole, where it predicts the existence of a nonsensical point of infinite density. Such a 'singularity' is screened from view by the horizon. The late Stephen Hawking suggested that General Relativity may also break down at the horizon of a black hole, and that the horizon might not actually be the surface of no return everyone believes it to be.

"We have not seen a departure from Einstein's theory yet," says Özel, "but finding such a discrepancy would be hugely important."

Einstein, who never actually believed that black holes could exist in reality, would have both been pleased that his theory has survived, and astonished that such a nightmarish prediction of this theory turns out to be real.

"The fact that Einstein's theory, formulated in 1915, so accurately predicts what we have seen in such an extreme environment, is a triumph for science," says Özel. "Until now, the horizon of a black hole was no more than a mathematical formula on piece of paper," she says. "Now it is a real thing in the real Universe."

LOOKING TO THE FUTURE

The long-term plan with the EHT is to observe Sagittarius A* and Powehi over many years, to see how they evolve as they swallow gas and rip apart stars. The hope is that we will get to understand things such as how they launch their jets. It is via these channels of super-fast matter – often accelerated to close to the speed of light – that supermassive black holes, despite their relatively tiny size, control the stellar content of their parent galaxies.

"We want to know whether the jets are launched at the horizon and how they are focused and collimated," says Özel.

In the 1990s, astronomers using NASA's Hubble Space Telescope in Earth orbit discovered that there is a supermassive black hole lurking in the heart of pretty much every galaxy. Why this is the case remains one of the great unsolved mysteries of cosmology, and it's one that's unlikely to be solved by the EHT. Other mysteries also persist. How quickly after the Big Bang were supermassive black holes born? Did they form in the hearts of newborn galaxies, or were they actually the seeds around which galaxies formed? Watch this space!

In the meantime, the first ever image of a black hole may look fuzzy, but sharper images will be obtained in the years to come. Very probably, it will go on to become one of the most iconic images in the history of science, alongside other famous pictures such as the Apollo 8 image of Earth rising above the Moon, or our first glimpse of the double spiral staircase of DNA.

"We humans should be proud of ourselves," says Özel. "It's easy to be overwhelmed by everyday events on Earth, but we should take some time to think, 'We have done this amazing thing. We have seen to the edge of space and time'."

ESO

ANATOMY OF A BLACK HOLE

1. ACCRETION DISK

The part of the black hole that gives away its location. Here, stars, gas and any other material nearby spiral towards the hole at blistering speeds, producing enormous amounts of electromagnetic radiation that we can detect here on Earth. The objects sucked into the black hole become more frantic and crowded as they near the event horizon. Some are dragged beyond this point into the hole itself, while others are blasted outwards to create a jet.

2. RELATIVISTIC JETS

Pop culture suggests that nothing escapes a black hole, but that's not quite true. Astronomers have observed jets of particles streaming out of black holes so long and fierce that they break out from their galaxy. To borrow an analogy from Konstantinos Gourgouliatos, a theoretical physicist at the University of Durham, this is like water coming out of a 1cm-wide hose pipe and travelling 80 per cent of the way across the Earth (that's 10,000km).

Our best models suggest that black holes twist the fabric of space-time at their poles. This effect coils magnetic fields, creating a cosmic corkscrew that accelerates particles close to the speed of light before firing them out into the void. At the same time, a magnetic dual-carriageway forms at the black hole's equator – this causes the magnetic field lines to twist and tangle, producing another particle accelerator effect.

These two effects create the fastest particles in the Universe, knocking at the door of the cosmic speed limit: the speed of light. In the long term, data from the EHT should help us understand this comic marvel in better detail.

3. PHOTON SPHERE

As material nears the event horizon, it emits photons (light particles). Normally these would travel outwards in straight lines, but at the cusp of the black hole its gravity bends the photon's path so that we observe a bright ring surrounding a spherical 'shadow'. The EHT will hopefully, in time, reveal more about both.

4. INNERMOST STABLE ORBIT

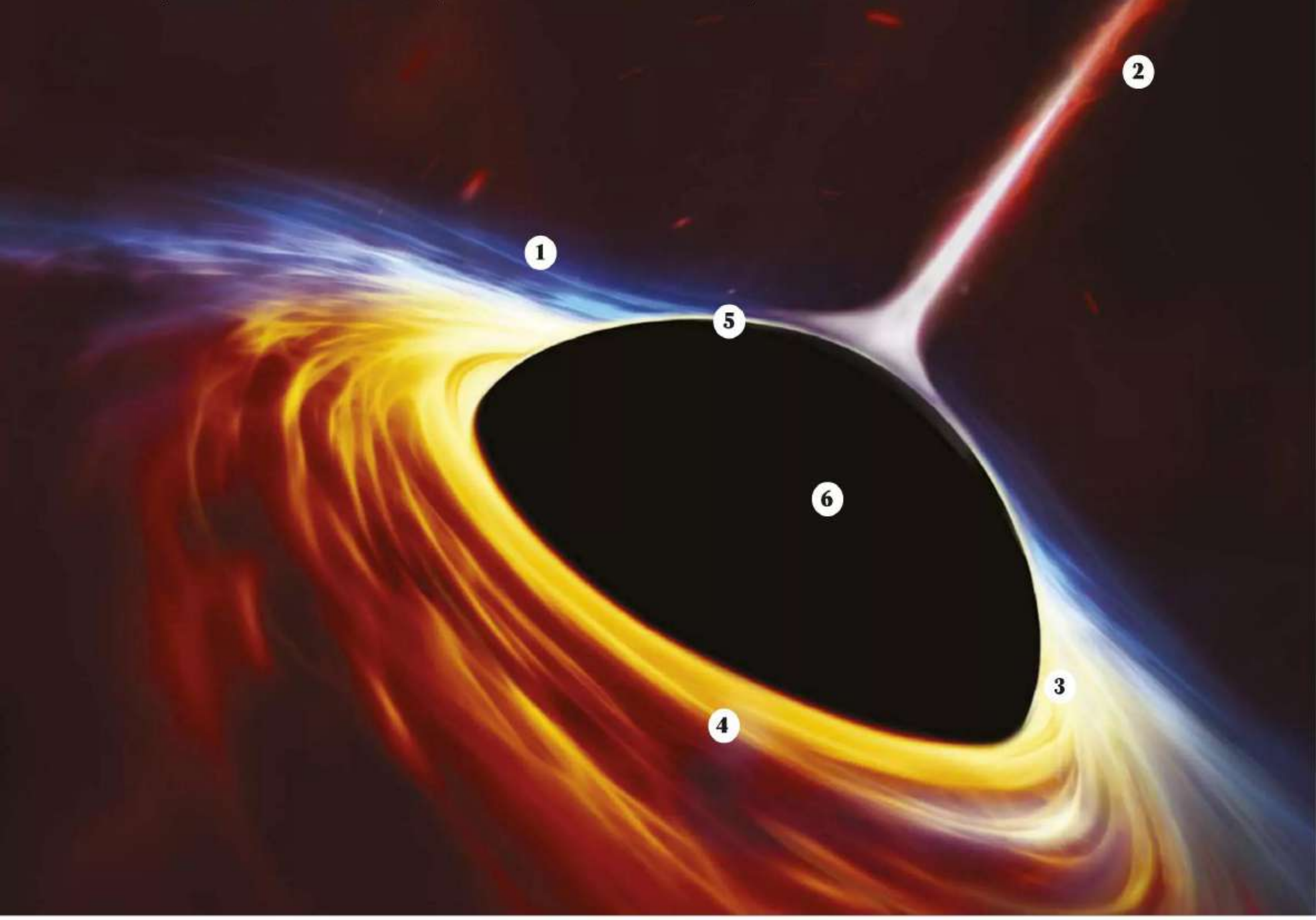
The inner edge of the accretion disk. This is the final region that material orbits before tumbling past the point of no return.

5. EVENT HORIZON

This is where the black part of the black hole begins. Beyond this point material cannot escape the black hole's grip. More accurately, the escape velocity needed to free itself from the hole's gravitational pull is greater than the speed of light.

6. SINGULARITY

All the matter and energy sucked into the black hole ends up here, at its centre: huge amounts of matter and energy are crushed into in an infinitely small space, giving rise to the black hole's gravitational pull. World-renowned theoretical physicist (and science consultant on the film *Interstellar*) Kip Thorne has described a singularity as "a location where the laws of physics break down."



HOW WE KNOW BLACK HOLES EXIST...

WHY HAVE PHYSICISTS BELIEVED FOR SO LONG IN OBJECTS THAT UNTIL NOW HAD NEVER BEEN SEEN?

Karl Schwarzschild was a professor of astronomy at Berlin Observatory who, on the outbreak of WWI, volunteered for the German army. He did not have to: he had a good job and was 40 years old. But he was Jewish, anti-Semitism was on the rise in Germany, and he wanted to prove that he was just as German as everyone else.

Schwarzschild ran a weather station in Belgium, calculated shell trajectories with an artillery battery in France and, at the end of 1915, found himself on the Eastern Front. There, he developed blisters in his mouth. They spread over the whole of his body and he was sent to a field hospital, where he was diagnosed with *Pemphigas vulgaris*, a rare autoimmune disease in which the immune system attacks the skin.

Schwarzschild knew it was serious because the skin is the largest organ. It is through the skin that heat is lost and so, when it is compromised, it is not possible to control body temperature. Also, the skin is a barrier against microorganisms and so, when that barrier is breached, a person is prone to life-threatening infection. The condition remains incurable today, although it can be treated with steroids. But in 1915 there was nothing.

To distract himself, Schwarzschild turned to physics. Back in Berlin, he had been aware that Albert Einstein was working on a revolutionary new theory of gravity. And when he learned that Einstein had presented it in four lectures in November 1915, he obtained and devoured a written summary.

"EINSTEIN WAS AMAZED TO RECEIVE A LETTER FROM THE EASTERN FRONT, AND EVEN MORE AMAZED TO FIND A SOLUTION TO HIS EQUATIONS"

FROM NEWTON TO EINSTEIN

Isaac Newton imagined that there was a force of gravity between the Sun and Earth, like an invisible tether that kept Earth trapped in orbit. Einstein realised this was incorrect. In fact, a massive body like the Sun creates a valley in the space-time around it, and Earth travels around the upper slopes of the valley like a roulette ball in a roulette wheel.

Einstein had replaced Newton's one equation describing gravity by 10. So working out how space-time is warped by a given mass was very difficult. But, incredibly, Schwarzschild found a formula for the valley-like space-time curvature caused by a spherical mass like a star. He sent it to Berlin. Einstein was amazed to receive a letter from the Eastern Front, and even more amazed to find a solution to his equations, which he had considered impossible. The following week he presented the results at the Prussian Academy.

But Schwarzschild had not finished.

ABOVE German astronomer and physicist Karl Schwarzschild

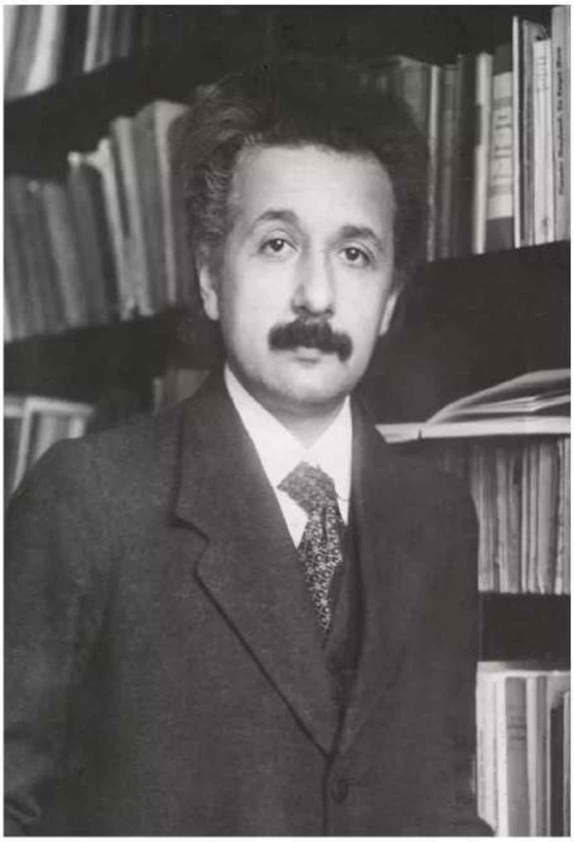
BELOW Physicist Albert Einstein

MONSTROUS ENTITY

Lying in his hospital bed, Schwarzschild further realised that, if the mass of a star was squeezed into a smaller and smaller volume, the valley of space-time around it would become steeper and steeper until eventually it would become a bottomless pit out of which nothing, not even light, could escape. Today, everyone in the world knows the name of what Schwarzschild had discovered but the term 'black hole' would not be coined for another half century. He again sent his solution to Einstein, who presented it in Berlin, although he did not believe nature would ever implement such a monstrous entity.

In the spring of 1916, Schwarzschild was moved to a hospital in Berlin, where he died. He was just 42.

The main problem in astronomy is that the Universe is big. There are two trillion galaxies, each with about 100 billion stars. Finding an interesting one is harder than finding an interesting sand grain among all the sand grains on Earth's beaches. What sign might reveal that a star was unusual?



Fast forward to 1971 and Herstmonceux Castle, the Sussex home of the Royal Greenwich Observatory. Paul Murdin was an astronomy researcher with a young family to support, and was in need of a permanent job. He had to make a name for himself, and he had an inkling of how to do it: by studying X-ray sources. Such high-energy light would be emitted by matter heated to millions of degrees. The previous year, NASA had launched Uhuru, the first satellite to survey the sky for X-ray sources, and Murdin obtained the catalogue.

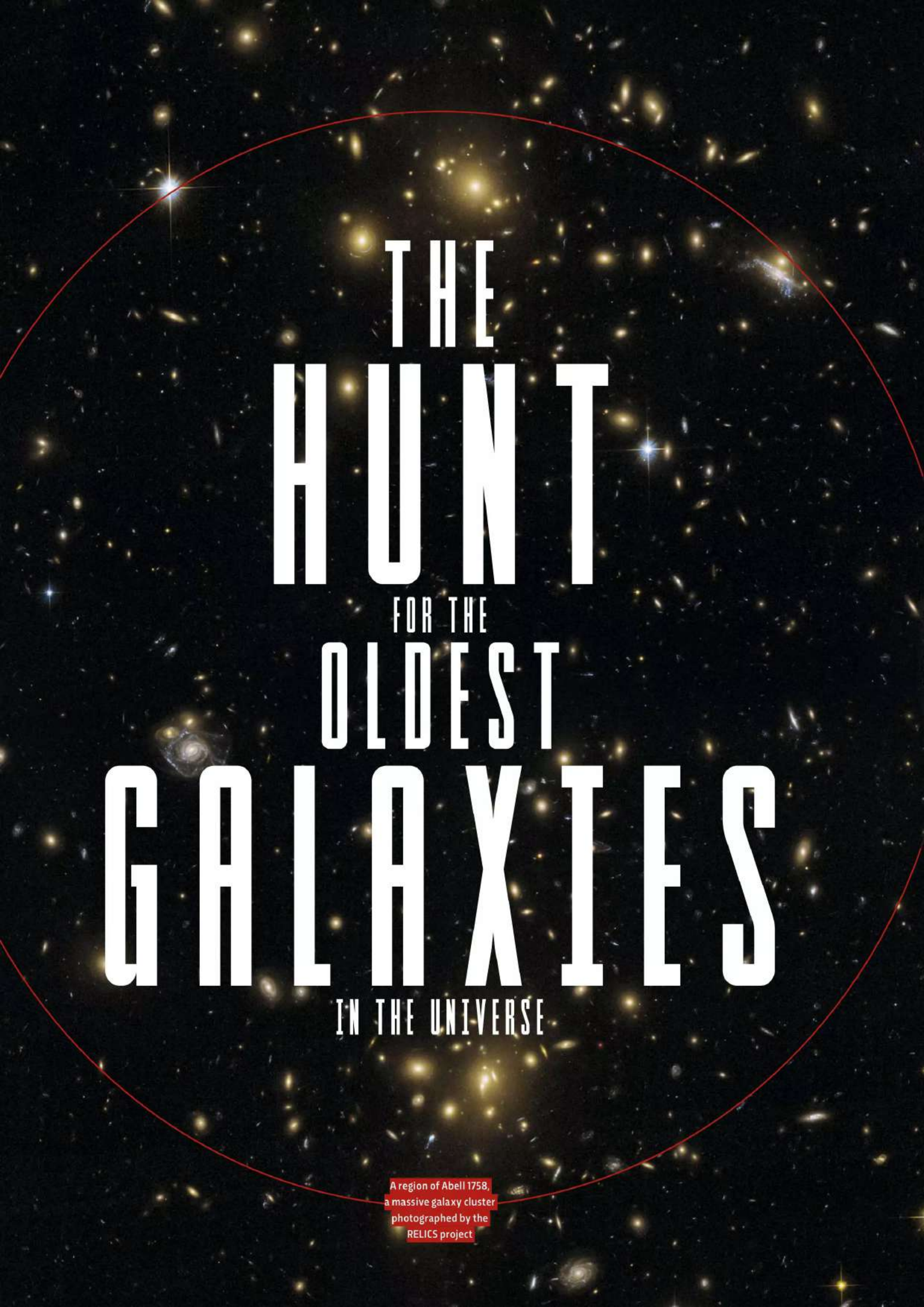
He noticed there was a bright X-ray source, christened Cygnus X-1, in the constellation of Cygnus. The only unusual star in the field was a blue supergiant called HDE 226868, many times the mass of the Sun and pumping out hundreds of thousands of times more light. The star could not be the source of the X-rays – but maybe it was orbiting something that was.

Murdin's colleague Louise Webster was measuring the speeds of stars, so he asked her to measure the speed of the blue supergiant. And, sure enough, she found it was orbiting an invisible companion, once every 5.6 days. From the speed that the supergiant was being whirled around, this companion had to have a mass of at least four, and probably six times the mass of the Sun. The only compact stars that were known – white dwarfs and neutron stars, the latter discovered by Jocelyn Bell Burnell only four years earlier – were not massive enough. Only one candidate remained: a black hole.

THEORY BECOMES REALITY

Incredibly, the monstrous, nightmare entity predicted by a man dying in a bed in a field hospital on the Eastern Front half a century earlier, actually existed in the real world! It was matter ripped from the blue supergiant and heated to incandescence as it was sucked down onto the black hole that was generating the X-rays. Murdin and Webster wrote a joint paper in the journal *Nature*. Murdin got his full-time job and a new house, and became the first person in history ever to have his mortgage paid by a black hole. **SF**

by MARCUS CHOWN
(@marcuschown)
Marcus is the author of Infinity In The Palm of Your Hand: Fifty Wonders That Reveal An Extraordinary Universe *(Michael O'Mara Books, 2018).*



THE HUNT FOR THE OLDEST GALAXIES IN THE UNIVERSE

A region of Abell 1758, a massive galaxy cluster photographed by the RELICS project

The deeper we look into the vastness of space, the further back in time we are able to see. Now, NASA's RELICS project is pushing this phenomenon as far as it can in an attempt to observe galaxies that formed at the very beginning of the Universe

by MARCUS CHOWN
(@marcuschown)

As the fireball of the Big Bang expanded and cooled, it went from white-hot to cherry-red before finally fading into invisibility. The Universe was plunged into blackness and the resulting cosmic dark age stretched on interminably. Over time, the Universe doubled in size, doubled once more, over and over again, then, one day, something extraordinary happened. The dark age came to an end. Across the entire length and breadth of the Universe, stars began switch on like lights on a Christmas tree.

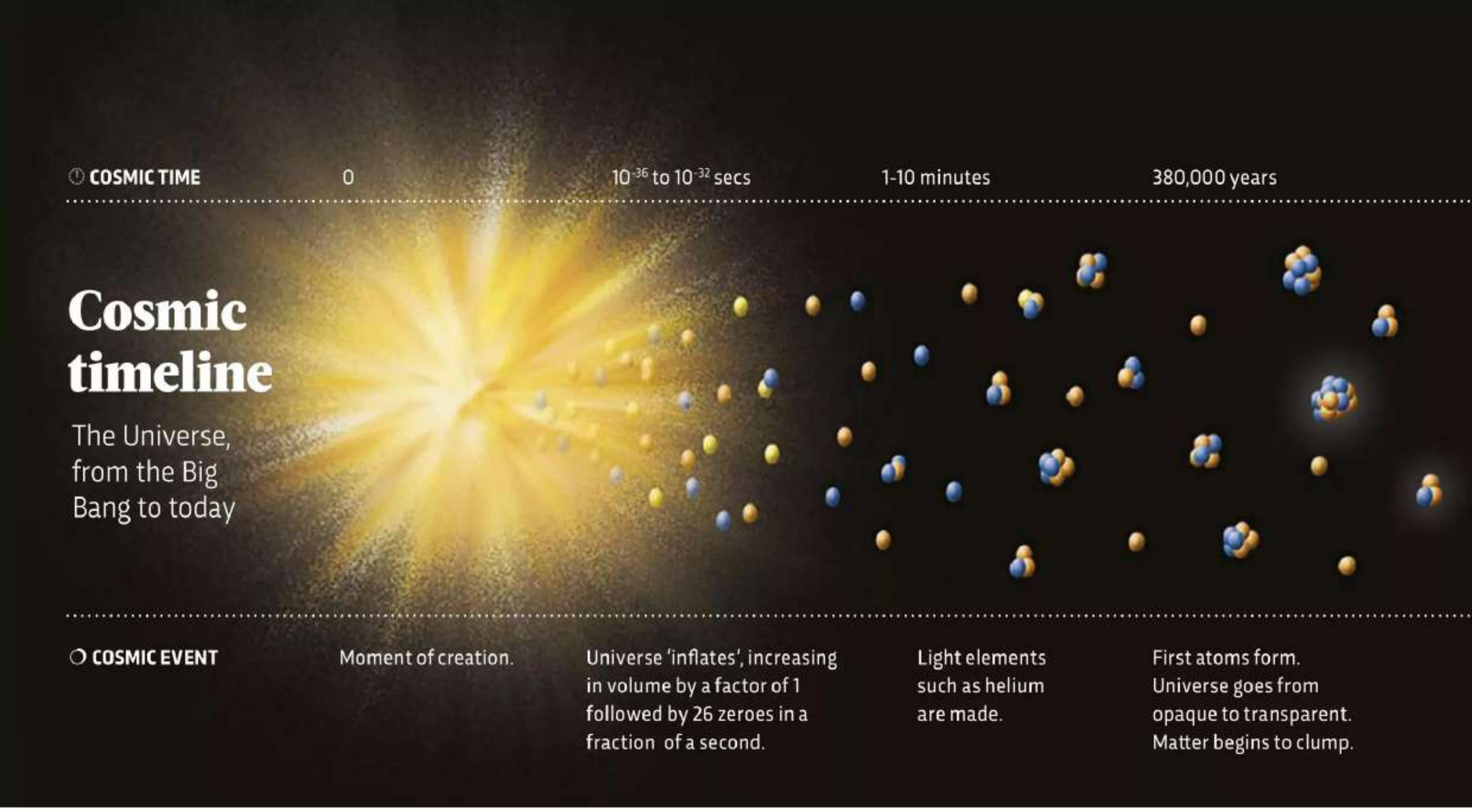
The first stars either came together under gravity to create the first galaxies, or were actually born in the clouds of gas and dust that made up the first galaxies. And the hunt to find these first galaxies is hotting up. One project – the Re-ionization Lensing Cluster Survey (RELICS) – has found around 300 galaxies that existed in the first billion years of the Universe's history. One galaxy in particular is so old that the Universe it occupied was a mere 3 per cent of its present age of 13.82 billion years. Such objects appear in astronomers' telescopes like persistent after-images, their light having travelled across space for billions upon billions of years before reaching us.

NASA/HUBBLE SPACE TELESCOPE

BACK IN TIME

More than 40 astronomers in many countries have been involved in the RELICS project, contributing hundreds of hours of observing time on the Hubble Space Telescope and the Spitzer Space Telescope. However, the principal observing instrument is the Universe itself. The gravitational fields of the massive clusters of galaxies that pepper the Universe act like giant lenses that focus and magnify the light of more distant galaxies that are often far too faint to see by any other means. "We take advantage of nature's own telescope," says Dan Coe, principal investigator of RELICS at the Space Telescope Science Institute in Baltimore.

To find the useful lensing clusters that would help him spot the oldest galaxies, Coe searched through Hubble's archive of images and a recent catalogue of around 1,000 galaxy clusters observed by the European Space Agency's (ESA's) Planck satellite. Planck's principal purpose was to image



the cosmic background radiation – the 'afterglow' of the Big Bang fireball itself – but the 'far-infrared' light it picked up also comes from warm dust in galaxy clusters. "We ended up with 41 massive galaxy clusters," says Coe. "We selected them for their extreme mass, which makes them enormously powerful gravitational lenses."

In the immediate neighbourhood of each cluster are literally thousands of ghostly images of distant galaxies that by chance have been 'gravitationally lensed' by the cluster. But most are of galaxies that are not at great distances, and so not in the very early Universe. "The trick to finding truly ancient objects is to look for lensed galaxies that appear in infrared images from Hubble and Spitzer images, but not in Hubble images taken at visible wavelengths," says Coe. But to understand *why* this reveals ultra-distant, ultra-early galaxies, we need to look at the concept of 'redshift'.

"THE MOST DISTANT GALAXY IN RELICS EXISTED OVER 13 BILLION YEARS AGO"

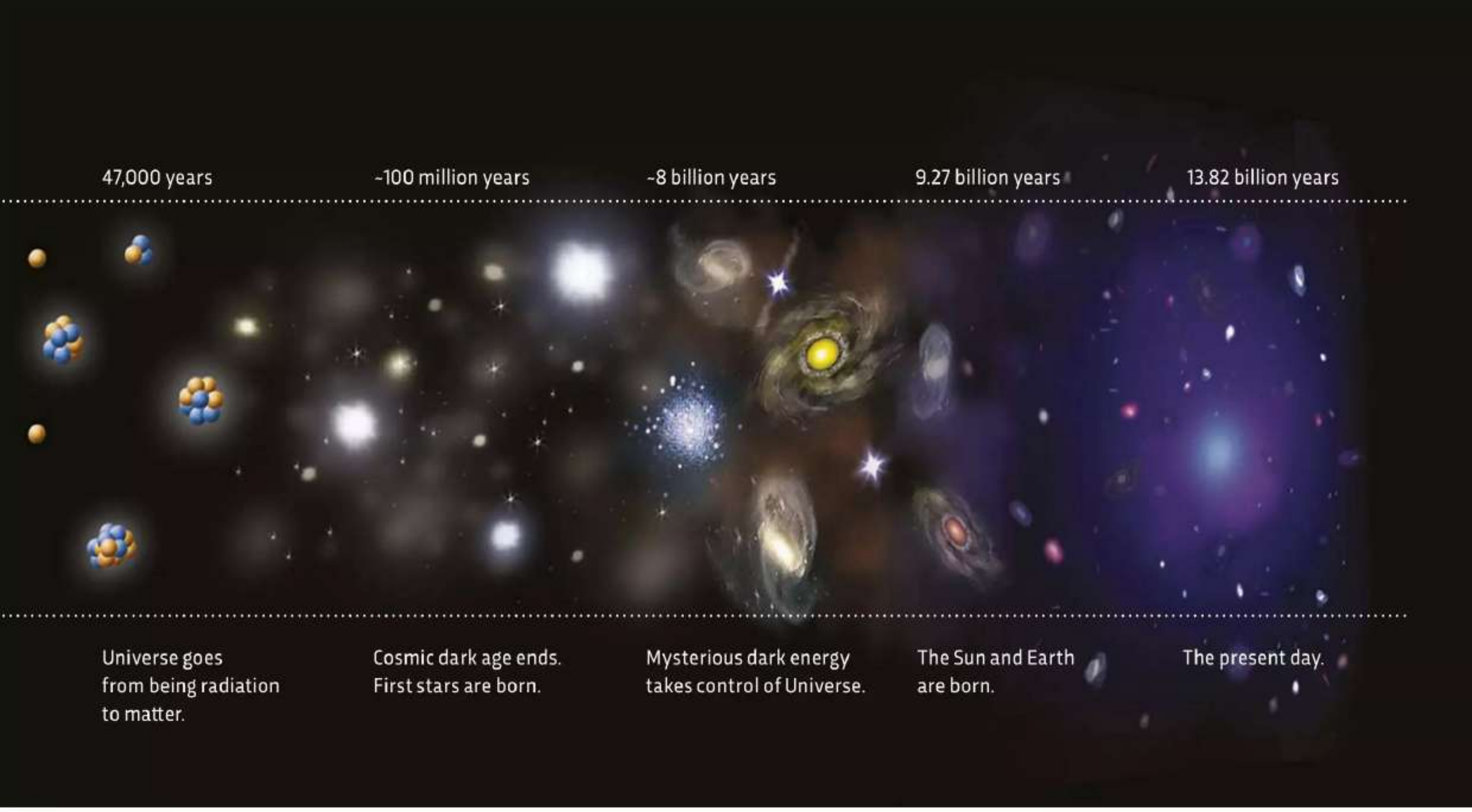
SEEING RED

When the Universe was younger, it was smaller. The most distant galaxy in RELICS existed more than 13 billion years ago when the Universe was less than one-thousandth of its current size. As space expanded over that time, it also stretched the light from that galaxy. Since red light has a longer wavelength than blue light, the light of such galaxies is shifted to the red end of the spectrum, or 'redshifted'.

The light of the earliest galaxies has been so severely redshifted that its visible light now appears as 'infrared', at wavelengths beyond the red end of the spectrum. Thus, the galaxies have the unique characteristic of being invisible to Hubble's Advanced Camera for Surveys but visible to Hubble's Wide Field Camera 3, which is sensitive to infrared light. Spitzer's infrared imaging instruments are also important in determining whether galaxies are at extremely high redshift, or less distant and merely intrinsically red due to dust or old age.

The gravitational lens formed by a galaxy cluster zooms in on a tiny region of the night sky so it might be expected that such a region would be more likely to contain empty space than any galaxies in the distant Universe. However, it turns out that galaxies in the early Universe were much smaller and a lot more numerous, so actually there is a good chance of them appearing in the field of view of any given gravitational lens. This explains why RELICS has found not a handful of galaxies, but around 300. These date back to the first billion years of the Universe and include

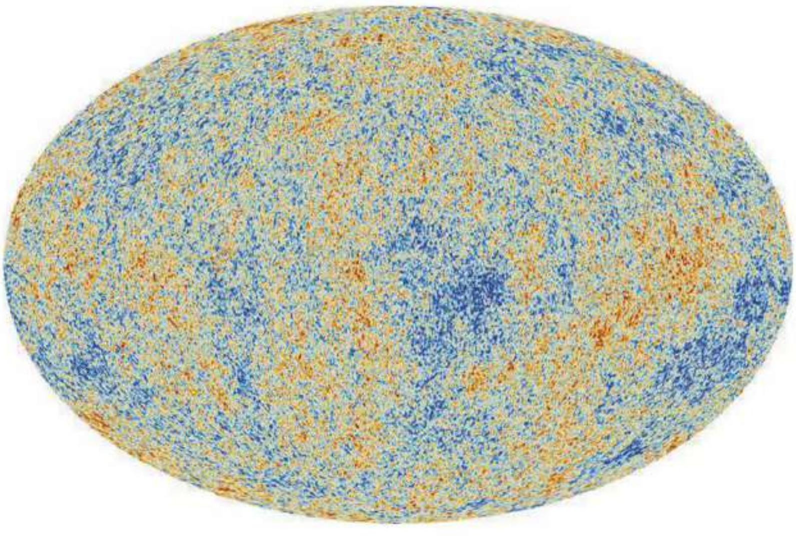
ESA X2



the brightest ones ever observed from that epoch.

Among the 300 galaxies is the rather unimaginatively named SPT0615-JD. It has a redshift of 10, which means it existed when the observable Universe was less than one-tenth of its current diameter and only about 400 million years old (the current record-holding galaxy, found in a previous survey, actually has a redshift of 11). The lensing effect has distorted the galaxy into an extended 'arc' and Coe says further observations will be needed to discern any details. Nevertheless, it is already obvious that SPT0615-JD is quite unlike a present-day galaxy. It is only one-twentieth of the diameter of the Milky Way, has less than one-hundredth of its mass, and none of its regularity. In fact, Coe and his colleagues refer to it as a 'smudge'. The other 300-odd galaxies are similarly small.

BELOW
Oval sky map of the cosmic microwave background (CMB), as seen by the Planck satellite. The CMB is radiation left over from shortly after the Big Bang. The different colours are tiny temperature differences, due to density variations after the Big Bang. Denser regions attracted more matter, leading to the formation of galaxies



If we had a time machine and could go back to a redshift of 10, we would find ourselves in a different Universe. There would be no galaxies with distinct structures like today's 'giant ellipticals' and 'spirals'. In their place we would see tiny, disordered blobs, often less than one-hundredth the diameter of the Milky Way. Such galaxies would be undergoing star formation at a ferocious rate, often hundreds or thousands of times faster than galaxies in today's Universe. There are at least two reasons for this. First, gas – the raw material of stars – was plentiful. Second, galaxies at a redshift of 10 were thousands of times more numerous than today's galaxies and far closer together, resulting in frequent collisions and mergers, which triggered intense bouts of star formation.

The fact that mergers were such a dominant feature of the early Universe may tell us something important about the galaxies of that time. "Very possibly, we are seeing the building blocks of today's galaxies," says Coe. "As time passed, these ancient galaxies were destined to collide and merge over and over again. In fact, our Milky Way could well have undergone thousands of such mergers to reach its current size."

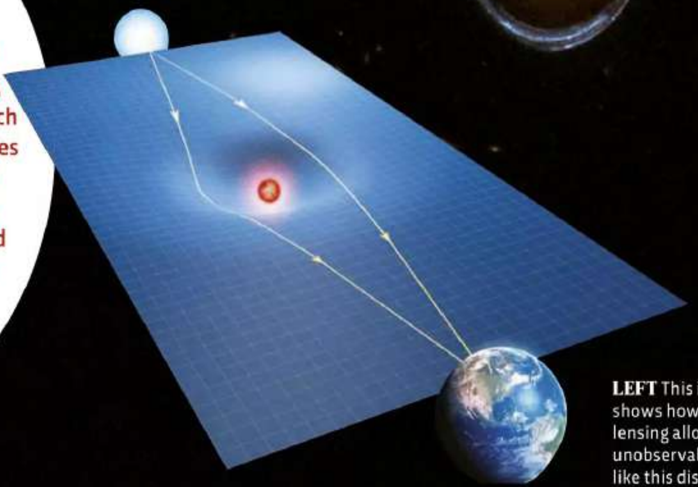
According to Coe, we have not yet seen the first galaxies, since even the earliest galaxies we've found contain older, bright red stars that are near the end of their lives. The first galaxies could conceivably have formed a mere 200 million years after the Big Bang. The best hope of finding them, says Coe, is by using the James

GRAVITATIONAL LENSING

HOW IT WORKS

Gravity bends the path of light, and was predicted by Einstein's General Relativity in 1915. Arthur Eddington confirmed it during a total eclipse of the Sun in 1919. Light-bending by gravity, now known as gravitational lensing, means that much of the distant Universe that we see without telescopes is an optical illusion. As light from distant galaxies travels towards us, it passes closer galaxies and is bent and focused. Sometimes this creates distorted arcs of the distant galaxies, sometimes multiple images. Such lensing acts as a telescope, enabling us to zoom in on bits of the Universe we would otherwise be unable to see.

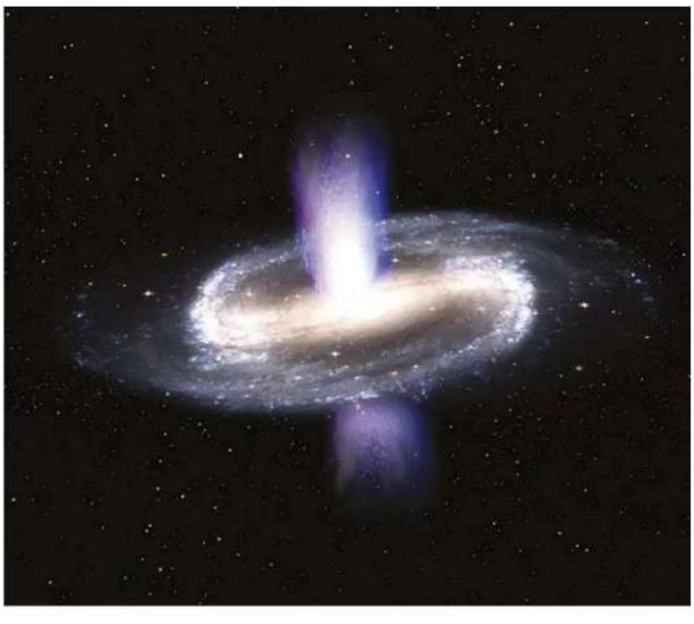
RIGHT The gravity of a red galaxy has distorted the light from a more distant blue galaxy, causing it to curve around



LEFT This illustration shows how gravitational lensing allows us to see unobservable objects, like this distant blue star

Webb Space Telescope, the successor of Hubble, which is due for launch in 2021. With its 6.5-metre primary mirror, it will orbit around the Sun at the so-called Lagrange-2 point, about a million kilometres from the Earth. Lagrange points are areas in space where gravity from the Sun and Earth balance out the orbital motion of a satellite. Placing a spacecraft at any of these points allows it to stay in a fixed position relative to the Earth and Sun with a minimal amount of energy needed to change its direction.

BELOW Supermassive black holes, like the one in this illustration, may have played a key role in transforming the nature of gas in the early Universe



DIGGING DEEPER

As James Webb will be sensitive to far-infrared light, it will be capable of detecting galaxies at ultra-high redshift. The hope is that the James Webb will shed light on 'cosmic re-ionisation', a key event which fundamentally changed the nature of the gas floating throughout space in the early Universe. About 380,000 years after the Big Bang, the fireball had cooled sufficiently for electrons to combine with hydrogen and helium nuclei to form the Universe's first atoms. However, there is a mystery. Today, when astronomers observe the hydrogen gas floating in space, they discover that its electrons have been blasted away – it has been 're-ionised'. The only thing that could have re-ionised the Universe is high-energy ultraviolet light. So where did it come from?

Planck observations indicate that re-ionisation began at a redshift of about 9. One possibility is that the responsible ultraviolet light came from the first stars, which may have started forming just 100 million years after the birth of the Universe. Another possibility is that the ultraviolet light came from matter heated to incandescence as it swirled down onto supermassive black holes. These formed in the hearts of newborn galaxies, causing them to shine as super-bright quasars. Coe thinks it's possible that multiple sources re-ionised the Universe. "Maybe stars are responsible for most of the re-ionisation and quasars for some,"

RIGHT
Engineers assemble the primary mirror of the James Webb Space Telescope, due for launch in 2021

he says. "And it is even conceivable that there might be another source – perhaps the annihilation of particles of dark matter, mysterious invisible stuff known to outweigh the stars and galaxies by a factor of six."

But the hope is that James Webb will help answer many more questions. Like when did the first stars form? Such Population III stars, as they are known, would have contained only hydrogen and helium from the Big Bang but no heavier elements such as oxygen, calcium and iron, which can be made only by nuclear reactions inside stars. Nobody has yet spotted any Population III stars, which are expected to have been much more massive than today's stars and raced through their lives at breakneck speed in only a few million years before detonating as supernovae.

Hubble has already spotted galaxies making the transition from amorphous blobs to ordered structures, rotating like the great spiral of the Milky Way, but James Webb may find the earliest galaxies that exhibited such ordered rotation. In fact, there is a possibility that Coe and his team may be able to determine this with follow-up observations using the Atacama Large Millimeter/submillimeter Array. If they can detect emission from oxygen in any of their ancient galaxies, differences in the frequency of that emission across the galaxies could reveal whether some parts are moving towards us and some away in a systematic way. Such a doppler effect is the smoking gun for galaxy rotation.

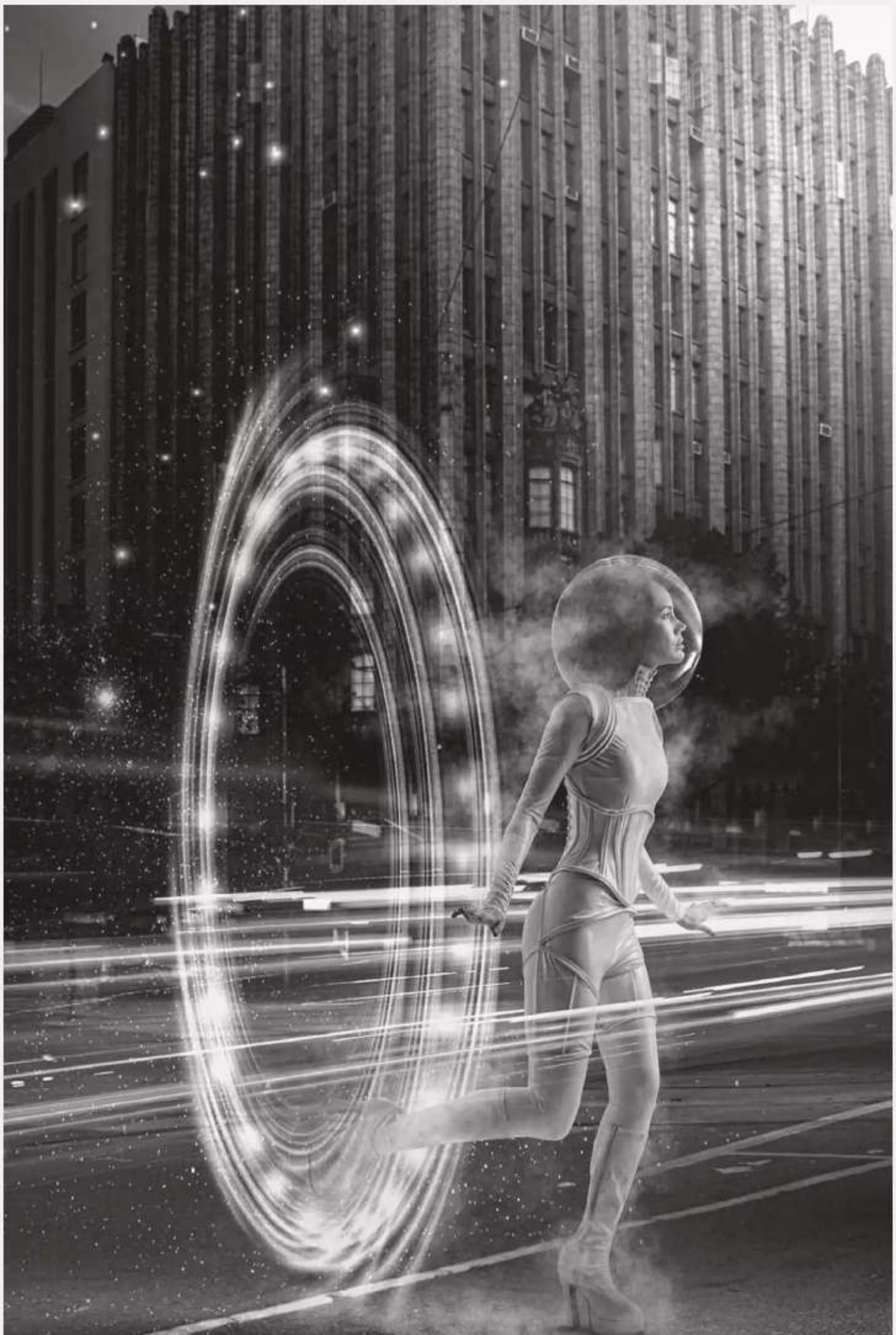
James Webb may settle other questions, such as when did the first galaxies form? What did they look like? Are they truly the building blocks of galaxies like the Milky Way? "We have observed galaxy evolution over 13.4 billion years of cosmic time – that's 97 per cent of the way back to the beginning," says Coe. "I am most excited to see the missing 3 per cent – the last remaining jigsaw piece." **SF**

"THE JAMES WEBB TELESCOPE MAY ALSO SETTLE OTHER QUESTIONS, SUCH AS WHEN DID THE FIRST GALAXIES FORM?"

by **MARCUS CHOWN** *(@marcuschown)*
Marcus is the author of Infinity In The Palm Of Your Hand *(£14.99, Michael O'Mara Books).*

Q&A

ALL YOUR QUESTIONS ANSWERED



IS IT THEORETICALLY POSSIBLE TO CREATE A WORMHOLE ON EARTH?

In 1935, Albert Einstein and his colleague Nathan Rosen showed that black holes can theoretically be connected via 'wormholes' – shortcuts through space and time that could link up black holes light-years apart. To create a wormhole on Earth, we'd first need a black hole. This is problematic: creating a black hole just a centimetre across would require crushing a mass roughly equal to that of the Earth down to this tiny size. Plus, in the 1960s theorists showed that wormholes would be incredibly unstable. It could be possible to stabilise the wormhole using so-called 'exotic matter', whose existence is predicted by quantum theory. This weird stuff is expected to have an antigravitational effect, which could stop the wormhole collapsing. But no one has a clue how to do any of this. And even if they did, it might all be pointless: theorists now suspect that travelling via wormholes would actually take longer than simply taking the conventional route through space.

COULD A MAGNET PULL AN OBJECT FROM A BLACK HOLE?

Astronomers have found that the magnetic field strengths near supermassive black holes can be as strong as their intense gravitational fields. These magnetic fields can expel material from around the black hole to form highly energetic outflows called 'jets'. However, this process is not acting on material that has already passed beyond the black hole's event horizon (where gravity is so strong not even light can escape). Such material would need to be accelerated to at least the speed of light to escape, and Einstein's General Relativity shows this would require an infinite amount of energy. No magnet, however powerful, could provide this.

HOW WOULD OUR SOLAR SYSTEM BE DIFFERENT IF JUPITER HAD BEEN BIG ENOUGH TO BE A STAR?

If Jupiter had carried on growing, it would eventually have become a star. If this star was a barely luminous 'brown dwarf', it would have only a minor effect on planetary orbits. But if it had become a more massive star, it would probably have prevented planets from forming in stable orbits. In any case, it would have greatly increased the amount of radiation their surfaces receive, so the development of life in our Solar System would have been far less likely.

GETTY IMAGES X3, NASA/JPL

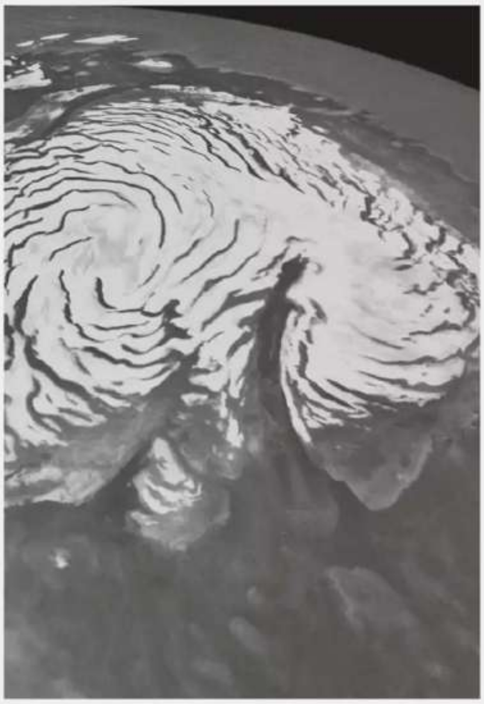
DOES THE MOON LOOK UPSIDE DOWN IN THE SOUTHERN HEMISPHERE?

Yes, the Moon does look 'upside down' in the southern hemisphere compared to the northern hemisphere. This is simply a matter of orientation. Imagine if the Moon orbited in the same plane as the equator. If you were in the northern hemisphere, the Moon would always appear in the southern sky, since that is the direction of the equator. The reverse is true in the southern hemisphere: the Moon would appear in the northern sky. So, these two observers are looking at the same object from opposite directions and naturally, one sees the object as flipped compared to the other.

The 'man in the Moon' appears upside down in the southern hemisphere and can look more like a rabbit.

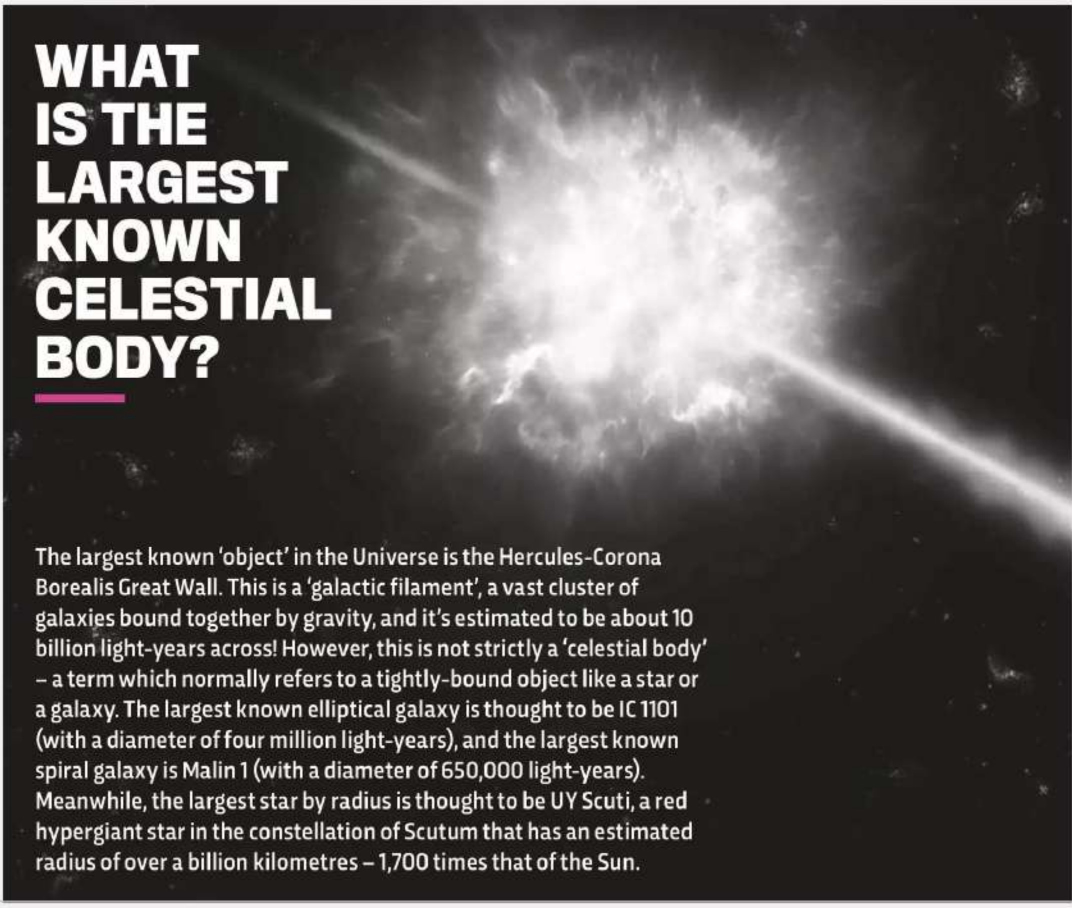
WHAT DOES MARTIAN WATER TASTE LIKE?

Most of Mars's water isn't present as liquid: it's ice, mixed in with the soil. Mars has such low atmospheric pressure that pure water ice sublimes directly from solid to gas without ever melting into liquid. There is evidence that the Red Planet may occasionally have some liquid water, but it would be undrinkably salty. If you distilled the water inside your pressurised habitat though, it would be quite safe to drink.



HOW HIGH COULD YOU JUMP ON OTHER BODIES?

	Mercury	Venus	Earth	Moon	Mars	Phobos	Ceres
Surface gravity	0.378G	0.91G	1.0G	0.166G	0.379G	0.00059G	0.0284G
Average person	30.2kg	72.8kg	80kg	13.3kg	30.3kg	0.0472kg	2.272kg



WHAT IS THE LARGEST KNOWN CELESTIAL BODY?

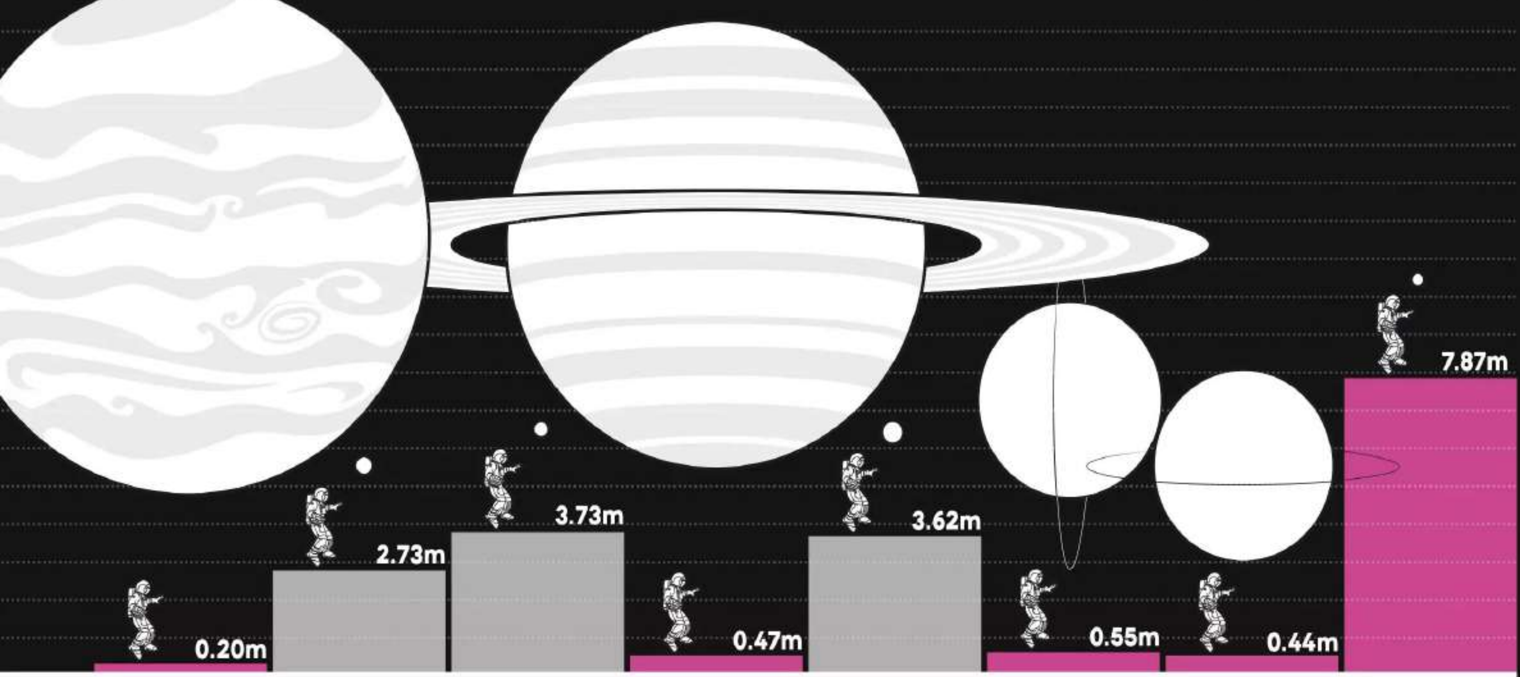
The largest known 'object' in the Universe is the Hercules-Corona Borealis Great Wall. This is a 'galactic filament', a vast cluster of galaxies bound together by gravity, and it's estimated to be about 10 billion light-years across! However, this is not strictly a 'celestial body' – a term which normally refers to a tightly-bound object like a star or a galaxy. The largest known elliptical galaxy is thought to be IC 1101 (with a diameter of four million light-years), and the largest known spiral galaxy is Malin 1 (with a diameter of 650,000 light-years). Meanwhile, the largest star by radius is thought to be UY Scuti, a red hypergiant star in the constellation of Scutum that has an estimated radius of over a billion kilometres – 1,700 times that of the Sun.

DOES THE SUN MAKE A SOUND?

The Sun generates sound in the form of pressure waves. These are produced by huge pockets of hot gas that rise from deep within the Sun, travelling at hundreds of thousands of miles per hour to eventually break through the solar surface. As a result, the Sun's atmosphere is seething like a pan of boiling water. The characteristics of sound waves, such as speed and amplitude, depend on the material they pass through and can be used to study the Sun's deep interior. Unfortunately, the wavelength of these waves is measured in hundreds of miles, so they're outside the range of human hearing.

GETTY IMAGES X2, A ROQUETTE/ESO

*Gas giants don't have a clearly defined surface



Jupiter*	Io	Europa	Saturn*	Titan	Uranus*	Neptune*	Pluto
2.53G	0.183G	0.134G	1.07G	0.138G	0.91G	1.14G	0.0635G
202.4kg	14.64kg	10.72kg	85.6kg	11.04kg	72.8kg	91.2kg	5.08kg

HOW FAR FROM EARTH COULD OUR RADIO SIGNALS BE DETECTED?

While commercial radio broadcasts began around 100 years ago, these early transmissions used frequencies that were either mopped up by the atmosphere or drowned out by radio emissions from the Sun. In contrast, military radar transmissions set up during the Cold War to detect incoming ballistic missiles have the power and frequency characteristics to be detected over hundreds of light-years – and have already broadcast our existence to any aliens within around 60 light-years of the Earth.

DOES EARTH HAVE A SECOND MOON?

There is only one permanent natural object that orbits the Earth: the Moon. Several small asteroids are 'quasi-satellites' of the Earth; from our perspective, they appear to follow a loop around our planet, but they are not actually orbiting us.

Occasionally, Earth captures an asteroid in a temporary orbit and these can be considered moons or 'minimoons'. One such object, the asteroid 2006 RH120, was a car-sized 'moon' of Earth that orbited from September 2006 to June 2007.


Some physicists think the Universe is just one of many

WHAT DOES SPACE SMELL LIKE?

We can't smell space directly, because our noses don't work in a vacuum. But astronauts aboard the ISS have reported a metallic aroma like welding fumes on their spacesuits following a spacewalk. The Rosetta spacecraft also detected compounds responsible for the smell of rotten eggs, bitter almonds and cat urine, boiling off the surface of comet 67P/Churyumov-Gerasimenko.

COULD WE EVER DETECT OTHER UNIVERSES?

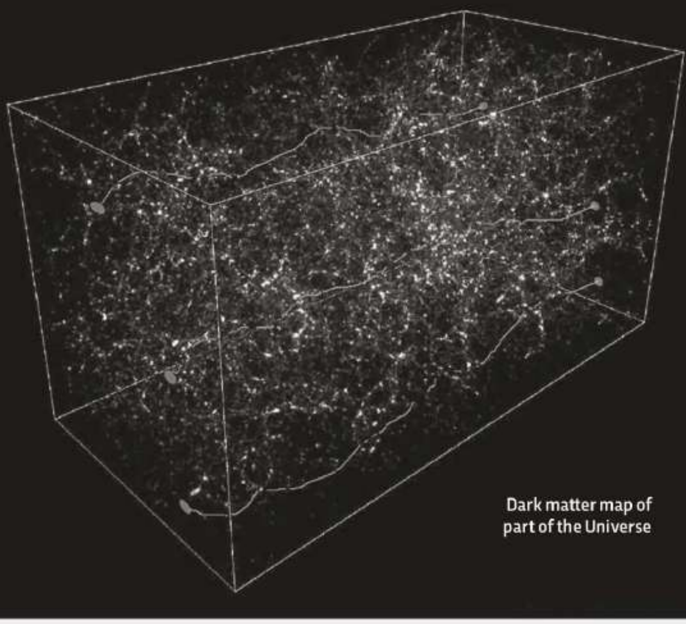
The idea that the Universe is one of many, making up one, truly infinite 'multiverse' is among the most intriguing – and controversial – theories in modern physics. It's based on attempts to find the one true 'Theory of Everything' (ToE) that describes all the particles and forces making up reality in a single set of equations. Some attempts to create the ToE suggest there are many different universes, each with different laws of physics. These differences may reveal the existence of universes neighbouring our own, but exactly how they'll be revealed is unclear. One possibility is via distortions in residual heat from the Big Bang. This has been precisely mapped and may contain patterns consistent with the lurking presence of another universe.

COULD THERE BE MATERIALS ON OTHER PLANETS THAT WE DON'T HAVE ON EARTH?

Yes, absolutely – because every so often, we get a delivery from meteorites. Chemical analysis has so far identified around 300 minerals from this deep space debris, including around 40 unique to these meteorites. One of the most intriguing materials was found in the Allende meteorite, which exploded over Mexico in 1969. After analysing the debris, scientists in 2012 announced the discovery of a material that not only has never been seen on Earth but wasn't even known to be possible. Named 'panguite' – after the giant Pan Gu who created the Earth in Chinese mythology – it consists of a bizarre mix of elements, including titanium, zirconium and scandium.

COULD DARK MATTER JUST BE DEAD STARS AND PLANETS FLOATING IN THE DEPTHS OF SPACE?

Some astronomers have indeed theorised that dark matter might just be ordinary matter that we cannot see, rather than an exotic, as-yet-undiscovered particle. This ordinary matter could include black holes, neutron stars, brown dwarfs, white dwarfs, faint red dwarfs and even solitary planets. These objects, collectively known as MACHOs (Massive Astrophysical Compact Halo Objects), emit very little light, but they can be detected if they pass in front of or near a background object (via the way that their gravity bends the light from the more distant object). However, studies to date have concluded that MACHOs can only account for a tiny fraction of the missing mass in the Universe. So the nature of dark matter remains a mystery.


Dark matter map of part of the Universe

GETTY IMAGES, NASA, SCIENCE PHOTO LIBRARY

Find out more about the missions that will help unravel the mysteries of the cosmos, from our closest neighbours to the galaxies far, far away.

FROM THE MAKERS OF ***BBC SCIENCE FOCUS*** MAGAZINE